University of Ottawa
Faculty of Graduate and Post-Doctoral Studies
M.Sc. Systems Science

Thesis

Multi-Criteria Decision Support for Strategic Program Prioritization at Defence Research and Development Canada

By:

Hami Ismaili

Thesis Supervisors: Dr. Daniel E. Lane
Dr. Kendall Wheaton

University of Ottawa
2013

Abstract

The objective of this thesis research is to model the multiple program objectives used by Defence Research and Development Canada (DRDC) for the annual management and allocation of their broad range of Science and Technology (S&T) projects in order to best achieve the strategic goals of the agency and the government.

This M.Sc. thesis presents methodologies, techniques and applications in Linear Programming (LP) and Multi-Criteria Decision Making (MCDM) for decision support in program prioritization and project selection of the DRDC S&T projects.

The results of this research produce a model that supports decision makers effectively in the assignment of limited human and financial resources to competing S&T projects based on the evaluation of projects that merit funding and the multiple criteria established by the organization. While there is a well-defined set of criteria for the annual program formulation process, the selection procedure is currently based on simple scoring processes and expert judgement; it lacks a well-defined and structured analysis. The application of an MCDM framework is proposed to take advantage of the well-structured problem and improve annual renewal and ongoing monitoring or project performance measures. The results of the analysis provide a traceable and rigorous MCDM framework to evaluate the performance of DRDC S&T projects for enhanced resource allocation.

Acknowledgements

I would like thank the following for their assistance and support throughout my studies:

Prof. Daniel Lane for the opportunity, guidance and advice during many revisions of this thesis and his patience with me as I developed my research skills. Without your encouragement and trust in me, this would have not been possible.

My co-supervisor Dr. Kendall Wheaton for his assistance in bringing my theoretical knowledge into perspective and investing a great deal of time to share his valuable experiences.

The examination committee: Prof. Wojtek Michalowski and Prof. Jacomo Corbo for reviewing this thesis and providing valuable and constructive comments.

Prof. Tet Yeap and Ms. Monique Walker for their guidance in the Systems Science program.

My parents, Aziz and Mehrangiz, for seeding the love of knowledge in me.

And my wife Nasim, for her love, encouragement and support.

"Regard man as a mine rich in gems of inestimable value.
Education can, alone, cause it to reveal its treasures,
and enable mankind to benefit therefrom."

TABLE OF CONTENTS

List of Figures

List of Tables

Glossary of Terms

ADM	Assistant Deputy Minister
AHP	Analytic Hierarchy Process
CF	Canadian Forces
CORA	Centre for Operational Research and Analysis
CPME	Collaborative Planning and Management Environment
DBI	Davies–Bouldin Index
DGSTO	Director General for Science and Technology Operations
DRDC	Defence Research and Development Canada
DND	Department of National Defence
DEE	Development, Engineering and Evaluation
EA	Evolutionary Algorithm
ELECTRE	Elimination Et Choix Traduisant la Realité
FPG	Functional Planning Guidance
FTE	Full Time Equivalent
GUI	Graphical User Interface
LDA	Linear Discriminant Analysis
LP	Linear Programming
MARCUS	Multi-criteria Analysis and Ranking Consensus Unified System
MCDM	Multi-Criteria Decision Making
MOU	Memorandum Of Understanding
MPA	Mutual Partner Agreement
NLP	Non-Linear Programming
PCA	Principal Component Analysis
PMF	Performance Management Framework
PG	Partner Group
PSST	Public Security Science and Technology
RPP	Report on Plans and Priorities
RTA	Research and Technology Analysis
S&T	Science and Technology
Thrust	Collection of similar projects grouped together
WPM	Weighted Product Model
WSM	Weighted Sum Model

1 Introduction

This thesis, in partial fulfillment of the Master's Program in Systems Science, provides a modeling framework to formulate and resolve a resource assignment problem at Defence Research and Development Canada (DRDC). DRDC is an agency of the Canadian Department of National Defence (DND) that responds to the scientific and technological needs of the Canadian Forces (CF) (DRDC, 2011a). The research is applied to the strategic planning and project selection process that occurs annually at DRDC Corporate Office in Ottawa.

This chapter describes the DRDC process for resource assignment and notes the characteristics that stimulated this thesis. This thesis surveys different methods of performing Linear Programming (LP) and Multi-Criteria Decision Making (MCDM) algorithms for the purpose of evaluating and improving project selection under constrained resources.

1.1 Background

Strategic program prioritization at DRDC is the subject of this thesis. Practical and efficient assignment of resources is an ever-challenging task in any organization. Government agencies are not an exception as they deal with a preset budget and pressure to make operations efficient and research costs minimal. This involves prioritization of funding for projects and selection of competing options with often conflicting criteria (Edmond, 2006). Inherent complexity due to the size of DRDC's projects requires a system that can perform ongoing monitoring and control. The DRDC problem is a strategic decision making process with high stakes, stochastic future implications, and involving many actors (Bhushan and Rai, 2004).

Since DRDC is always looking to improve its resource assignment practices, this research proposes techniques to capture the essential aspects of the DRDC's Science and Technology (S&T) program in a model. It then formulates responses in order to structure and enhance the decision making toward achieving the objectives of DRDC and the Government of Canada.

DRDC conducts S&T projects primarily for the Department of National Defence (DND) and the Canadian Forces (CF) arranged annually through Mutual Partner Agreements (MPA) with various groups of stakeholders. During the annual planning process, DRDC examines the progress of projects (which are mostly multi-year ventures) and evaluates the S&T program's strength to address priorities and objectives. Various categories of S&T projects are rated against expectations and the overall characteristics of DRDC's program and their qualities are subjectively evaluated and quantified (Wheaton and Bayly, 2010).

The framework for the assessment is prepared annually by the Director General for S&T Operations (DGSTO). In 2010, the framework consisted of four evaluated categories for projects: alignment, balance, synchronization and performance. Performance is defined through DRDC's internal Performance Management Framework (PMF) exercise. This analysis is based on the judgement of the senior DRDC managers and uses the PMF-defined criteria.

The findings of this analysis are presented as the Program Synopsis, which is an assessment on the business plans produced in 2010 by the Director General of S&T Operations (DGSTO) for the Assistant Deputy Minister (ADM) for Science and Technology and as reported by Wheaton and Bayly (2010).

DGSTO would like to enhance the S&T program formulation process used by DRDC's managers through better guidelines and a more structured allocation process. The intent is to allocate resources to keep the balance between various project categories while addressing deficiencies as priorities and objectives evolve.

DRDC's mandate

DRDC's mission is to ensure that CF is technologically prepared and relevant by providing technical support to a wide range of groups within DND and the CF (DRDC 2010a). Scientific projects are managed by DRDC for DND and the CF through two programs:

1. the Research, Technology and Analysis (RTA) program and
2. the Development, Engineering and Evaluation (DEE) program.

DRDC also provides S&T support to 21 other federal government departments through the Public Security Science and Technology (PSST) program. A memorandum of understanding (MOU) between DND and Public Safety and Emergency Management Canada, makes DRDC responsible for the S&T support to Public Safety Canada (DRDC CORA, 2010).

The annual business planning process conducted by DRDC produces six Mutual Partner Agreements (MPAs) for the RTA/DEE programs, a business plan for the PSST, and another business plan for the corporate management and services of DRDC.

During the annual business planning process, DRDC evaluates the program's alignment with government objectives to decide whether the S&T program is on the right track. The following criteria are utilized to define the goals of the S&T program (Wheaton and Bayly, 2010):

- Support key priorities and objectives;
- Demonstrate S&T relevance and utility across all the planning horizons; and
- Support strategic departmental initiatives.

1.2 Thesis objectives

It is acknowledged that the complex annual budget planning at DRDC could benefit from a more structured and analysis-based approach to allocate resources more effectively. To this end, the objective of this thesis is to accomplish the following research tasks:

1. To formulate the annual planning process into a model that captures all of the problem's salient characteristics.
2. To develop an applied evaluative method to improve DRDC's S&T program allocation structure.
3. To provide a framework to implement and test the model.

1.3 Outline of the Thesis

This thesis consists of five main parts:

Literature review: Chapter 2 discusses the current practices and methods that are used to evaluate similar problems of program allocation. Alternative methods that contribute to developing a solution to the problem are presented and critiqued with respect to the applied DRDC S&T allocation program. The objective of this review is to demonstrate a capacity to apply the alternative methods and to analyse their attributes and determine whether they can be applied to the problem at hand.

Methodology: Chapter 3 presents the methods that are selected from the literature review and deemed practical and applicable to address the problem. Application of the methods is explored. The process of extracting information about the current and past projects at DRDC is discussed.

Results and Analysis: Chapter 4 presents the outcomes and results of the application of the applied methodologies to structure the DRDC S&T problem. A comparison between the proposed methods is presented and improvements are also discussed with respect to the current process.

Conclusion and Recommendations: The last chapter, Chapter 5, summarizes the findings of the results and discusses future work.

The thesis also includes the following components:

Bibliography: Containing the list of published resources consulted and directly quoted in the proposal.

Appendices: These sections include the full details of the data gathered and produced throughout the various stages of the research.

2 Literature review

This chapter provides insight into methods and techniques currently used in published literature to evaluate problems in industry and government agencies that share the same challenges as the DRDC S&T annual allocation problem. Such organizations are often faced with the problem of selection and prioritization of programs or projects on an ongoing basis. The current practice at DRDC for program evaluation is presented and described in further detail in section 2.1 below. There are many techniques and methods applied in private and public sectors for making decision with regard to selection of projects (Mahmoodzadeh et al., 2007). Based on current trends in the industry today, Linear Programming (LP) (section 2.2) and Multi-Criteria Decision Making (MCDM) (section 2.3) are described as contributors to a solution to the problem at hand as a decision support mechanism.

2.1 Current Practice at DRDC for Program Prioritization

This section reviews the program formulation process as described in the Program Synopsis. The Program Synopsis is a document that was developed in 2010 for the first time to assess the overall condition of the S&T program (Wheaton and Bayly, 2010).

In DRDC, similar projects are collectively called a "Thrust". The term Thrust is used extensively in this thesis to refer to a collection of projects that are grouped together by DRDC for operational reasons. A Partner Group (PG) is designated as a group of Thrusts aligned with a segment of DND/CF.

The focus of the Program Synopsis is placed on the performance of a PG with respect to various criteria. It provides insight into the alignment of S&T in DND with government objectives. As described in its introduction it answers this question: "Is this the right S&T program to meet stakeholder priorities and expectations and how can it be improved?" (Wheaton and Bayly, 2010: p. ii).

The Program Synopsis was applied by the Director General for S&T Operations (DGSTO) with guidance from ADM(S&T). Feedback was provided on all aspects of the S&T Program by Directors and Director Generals across DRDC. The Program Synopsis is a key applied reference for this thesis. It describes the analysis that was performed by DRDC to assess how well the business plans had been prepared for 2010.

The following are the four elements that were examined to demonstrate the quality of the programs:

- Alignment to government objectives – refer to the objectives described in the ADM(S&T) Functional Planning Guidance (FPG) (DRDC, 2010b). The analysis indicates whether the efforts in S&T support the desired outcomes and meet priorities.

- Balance – refers to logical distribution of efforts in different categories. Gaps indicating insufficient or too much focus are clarified.
- Synchronization – refers to coordination with departmental activities to accurate and timely delivery of outcomes
- Performance Management Framework (PMF) – developed to evaluate projects with respect to quality, exploitability, and the leveraging of external partners.

The findings of the report were tabulated displaying the PGs with respect to the 4 criteria that show the quality of the S&T program. The data were acquired through feedback of project management teams and DRDC project database.

The Program Synopsis provides an accurate indication of the health of the S&T Program displaying its strengths and weaknesses. However, it does not provide direct guidance on the distribution of human resources and funding to improve issues that are observed with alignment, balance, synchronization and the PMF.

Program Synopsis brought to light the areas where more focus is required or too much effort is being placed. This research complements Program Synopsis as DRDC would like to further provide PGs with specific guidelines as to how to reallocate their resources to obtain better results. The output of this research is complementary to and supports the DRDC Program Synopsis. As the Program Synopsis determined the areas where more focus is required, this research quantifies the amount of resource reallocation from and to the various Thrusts in the DRDC program.

2.2 Linear Programming (LP) in Optimization of Strategic Programs

The general purpose of Linear Programming (LP) optimization is to determine how to distribute constrained resources in order to optimize a single objective, e.g., maximize profit or minimize cost. LP searches for the best way to utilize scarce resources to achieve the problem's quantifiable objective (Ragsdale, 2001). In DRDC's case, the objective is to maximize the programs' positive outcome towards strategic goals subject to utilizing the lowest "cost" which includes the human and financial resources.

LP was developed in 1940s as part of classified work during World War II, and received major improvements by George Dantzig's simplex method who utilized linear algebra methods to determine linear problem solutions (Eiselt and Sandblom, 2007). LP's rapid developments in the post-war 1950s along with advancement of computer technology, resulted in LP becoming one of the most widely used methods for planning and scheduling methods in operations research today (Dantzig and Thapa, 2003).

A linear programming optimization problem consists of a single objective function and equations and inequalities which serve as constraints (Ragsdale, 2001). In the DRDC's case, there are limited human resources and financial support and the objective may be stated to maximize overall programs "profit" (i.e., expected positive outcomes). Therefore, this problem may be dealt with through Linear Programming (LP), or linear optimization.

The mechanism of LP's algorithm allows a quick search for the optimum solution through the Simplex Method. The idea is to reduce the set of possible optimal solutions that need to be tested (Dantzig, 1968). However, in reality, even with the usage of the Simplex Method, large scale cases require computer technology and software to produce a feasible solution within an acceptable timeframe (Stevenson, 2008).

LP has been applied in telecommunications, portfolio optimization, scheduling, manufacturing and transportation in private and in the public sector (Ragsdale, 2001). It plays a major role in financial optimization decision support, due to its convenient solvability. These types of problems are constructed so that they have to meet many side constraints and cost restrictions (Mansini, 2003). LP has also been applied to many profit-maximization, allocation and assignment problems (Simonnard, 1966 and Anderson et al., 1995). Eiselt and Sandblom (2007) have also illustrated many examples in scheduling, inventory planning, transportation, allocation and data envelopment analysis.

2.2.1 LP Model Structure

To construct a model that can be solved by linear programming, the following elements must be defined (Ragsdale, 2001; Stevenson, 2008; Eiselt and Sandblom, 2007):

Decision variables: values that can be adjusted and are under the control of the system operator. For example, for the DRDC problem, the number of Full-Time Equivalents (FTE) that are assigned to a certain project and the amount of cash awarded to a project group (referred to as a *Thrust* in DRDC documents) are values that can be adjusted in order to achieve government objectives.

Objective function: the single-valued goal that maps the relationship of the objective as a function of the decision variables. The Objective Function is represented by a linear mathematical formula in the variables. The objective function is to be optimized by adjusting the decision variables subject to the constraints.

Constraints: a set of equations and/or inequalities involving the decision variables and defining the limited resources of the problem as restrictions on the set of values that can be assigned to decision variables. Constraints effectively impose upper and lower bounds on the decision variables and define a feasible region within the solution space. For example, in the DRDC case, the total number of FTEs with specialization in complex systems is considered a constraint. A feasible solution should not contain a value higher than the total number of FTEs available.

2.2.2 LP Optimization Methods

There are various techniques for solving LP problems. The most well-known are the graphical method, Dantzig's Simplex Method, and Karmarkar's exterior point method (Stevenson, 2010). The graphical solution is used to solve simple problems with only 2 decision variables. LP problems of sizable dimensions (e.g., 10s or 100s of variables and constraints) require greater computational power (Bunn, 1982).

LPs are known to handle very large systems nowadays with 1000s of variables and constraints. There are many software packages that provide support in solving such problems (Lane, 2007). Therefore with computers helping out with the computation, the main challenge remains to be the problem formulation, translating the problem statement into mathematical representations, and interpreting the output.

Some software applications are simply delivered as add-ins to other programs with easy user interfaces. "What's*Best!*" by Lindo Systems Inc., uses MS Excel as its input platform for equations, inequalities and other related data (Lindo Systems, 2011). Another built in add-in for MS Excel is '*Solver*', however its capacity to handle large-sized problems is limited. Due to the large scale of decision variables and constraints that define the size of the LP for the DRDC problem, i.e., assigning various resources to some 400 projects, a version of *What'sBest!* that can work with up to 8000 decision variables and 4000 constraints is used in this thesis to solve the DRDC LP. There are also many open-source freeware packages available such as OpenOpt (OpenOpt, 2012), Pyomo (COOPR, 2012), and JOptimizer (JOptimizer, 2012).

2.3 Multi-Criteria Decision Making (MCDM)

Multi-Criteria Decision Making (MCDM) is a process through which a discrete set of alternatives are ranked based on the alternatives' overall performance with respect to the weighted criteria. MCDM has become a popular solution methodology when the problem consists of alternatives and multiple criteria that are sometimes in conflict with each other (Phillips-Wren et al., 2008). The decision making methods are there to support decision makers' choices, not to provide the direct solution or eliminate the required decision making exercise and oversight (Mallach 1994).

In MCDM, the discrete alternatives are pre-selected. The decision support process simply ranks these alternative solutions. Therefore MCDM is applicable to the DRDC problem as it too deals with existing alternatives as solution options.

There exist a variety of MCDM methods and it is important to know that applying different MCDM algorithms can lead to different outcomes. Moreover, there is no single dominant MCDM method that performs better than all the other methods in all problem aspects (Triantaphyllou, 2000 and Hobbs and Meier, 2000).

Among various MCDM methods are included the following: Weighted Sum Model (WSM), Weighted Product Model (WPM), the Analytic Hierarchy Process (AHP and pairwise comparison to evaluate tradeoffs, Saaty, 2001), ELECTRE (outranking method of elimination and choice translating reality, Roy, 1968) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution, Bhushan and Rai, 2004). There are also variations of each that claim to have addressed some of their shortcomings such as revised AHP (Belton and Gear 1983), adaptive AHP (Davies, 2001) and fuzzy AHP (Van Laarhoven and Pedrycz, 1983 and Boender et al., 1989).

There are different ways to classify MCDM methods and problems, e.g., according to the data and the numbers of decision makers. The type of data being used in the problem may be: deterministic, stochastic or fuzzy. The number of decisions makers involved may be single decision makers, or multiple participant group decision makers (Triantaphyllou, 2000).

2.3.1 MCDM Terminologies

Common terminologies used in MCDM techniques are itemized below (Triantaphyllou, 2000):

Alternatives: the discrete set of different choices of action for decision makers' consideration. These choices are processed, evaluated, and eventually ranked.

Attributes: the discrete set of multiple decision criteria of the problem are identified as attributes of each alternative. Each attribute represents a different dimension from which the alternative can be evaluated (i.e., budget requirements (cost), quality).

Decision hierarchy: a representation of the main objective, criteria (attributes), subcriteria and the alternatives. The tree-shaped hierarchical graph represents the layered relationship between these elements which is used to compute the relative importance of each with respect to the main objective.

Conflict among criteria: it is possible for the criteria to be in conflict with each other (i.e., lower costs versus higher profits, or minimize costs of travel versus minimize time to destination).

Incommensurable units: it is not uncommon for various criteria to have different units of measure (e.g., cost in dollars versus time in months).

Criteria weights: in the real world, criteria have different levels of relative importance. This relative importance is represented by a value, or a weight, to indicate the relative effect of the dimension on the decision alternatives.

Data Grid: refers to a matrix containing the scores of each alternative with respect to each criterion. These matrices provide ease of calculations and are used widely in all MCDM methods.

Dominance: if an alternative is ranked higher than a second alternative across all scores, then it is said that the first alternative dominates the second.

2.3.2 MCDM Model

Following are typical set of steps involving the above terminologies toward constructing a model for the problem in MCDM (Triantaphyllou, 2000):

1- Determine the discrete criteria and construct the decision hierarchy
2- Identify the decision alternatives
3- Construct the data grid matrix (alternatives' scores) and decision weights (weighted hierarchy)
4- Assign numerical values to the matrices in step 3 above
5- Utilize a comparative algorithm to process the numerical values and output a relative ranking for each alternative

The algorithm used in step 5 depends on the MCDM method being applied and can result in different outcomes. AHP is one of the most applied and well-known MCDM techniques primarily due to its ease of application and because of its ability to manage qualitative as well as quantitative data (Saaty 2001). ELECTRE (Roy, 1968) is an outranking MCDM algorithm that is also investigated as a possible solution. Another MCDM method discussed in the literature review is MARCUS which is developed at DRDC and enjoys DRDC decision makers' confidence in its capabilities (Edmond, 2006).

Simon (1960) states that every decision must go through three phases: intelligence, design and choice. The emphasis on each phase and the relationship between the phases is different in each MCDM method and also in each different scenario. The intelligence phase consists of identifying and formulating the problem (steps 1 and 2 above). The design phase includes developing alternatives where the choice phase evaluates them to select a decision (steps 3 and 4 above). Then the choices can be processed where the most appropriate is selected (step 5 above).

The following subsections review the AHP (Analytic Hierarchy Process), ELECTRE (ELimination Et Choix Traduisant la REalité), GRIP (Generalized Regression with Intensities of Preference) and MARCUS (Multi-criteria Analysis and Ranking Consensus Unified System) as specific examples of applied MCDM models that may be useful for the DRDC S&T allocation problem.

2.3.3 AHP

AHP (Analytic Hierarchy Process) was proposed by Saaty (1980) in the early 1970s and has found many practical applications. It is based on decomposing a complicated problem into a system of hierarchies of sub-problems, which are analyzed independently and then the results are aggregated to produce the overall ranking of alternatives. The idea is to sub-divide and structure the problem into smaller problems that are mathematically easier to compare, analyze, and control (Bouyssou et al., 2000). Saaty (2008) has discussed numerous applications of AHP by various public and private sector organizations in problems such as selection of vendors, fund allocation to projects and selection of oil platforms. Fui and Sheng (2011) explain usage of AHP in Singaporean Defence Science and Technology Agency's (DSTA). DSTA has validated the effectiveness of the AHP framework through its procurement process for evaluation of defence systems. DSTA has provided consultancy to other government agencies for application of AHP to non-defence government projects. Raczynski (2008) applied AHP to a science and technology planning exercise conducted by the United States Navy.

The fundamental and initial step in the AHP is designing the hierarchical structure to make the problem well perceived by decision makers. Figure 1 shows a partial structure of the DRDC problem displayed in AHP hierarchy. It consists of the DRDC goal at the top followed by the high-level criteria on the second level. The third level consists of the breakdown of each criterion and finally the alternatives are at the bottom of the hierarchy.

The components in Figure 1 are extracted from DRDC's database as a partial arrangement of the DRDC problem hierarchy. The goal is the overall efficiency of the DRDC S&T program which is placed at the top of the hierarchy. Two of the high level criteria that directly contribute to the goal are placed at the second level, namely Project Design and Accountability. The criteria are further defined by other measures, termed subcriteria. These subcriteria are used in the scoring of projects' progress and performance. The alternatives in Figure 1 are three groups of Project Sets 1, 2 and 3 (located at the bottom of the hierarchy).

There are advantages of using a hierarchy in most complex problems. The structure can help to explain how changes in priority at higher levels affect the priorities in the lower levels. Building a hierarchy provides the opportunity to deconstruct a complex problem into the details of its system components and multiple objectives. Furthermore, most systems are structured hierarchically, making this method intuitive. Also, stability and flexibility in a well-constructed hierarchy is an attractive quality in future restructuring exercises of the problem (Saaty, 1980).

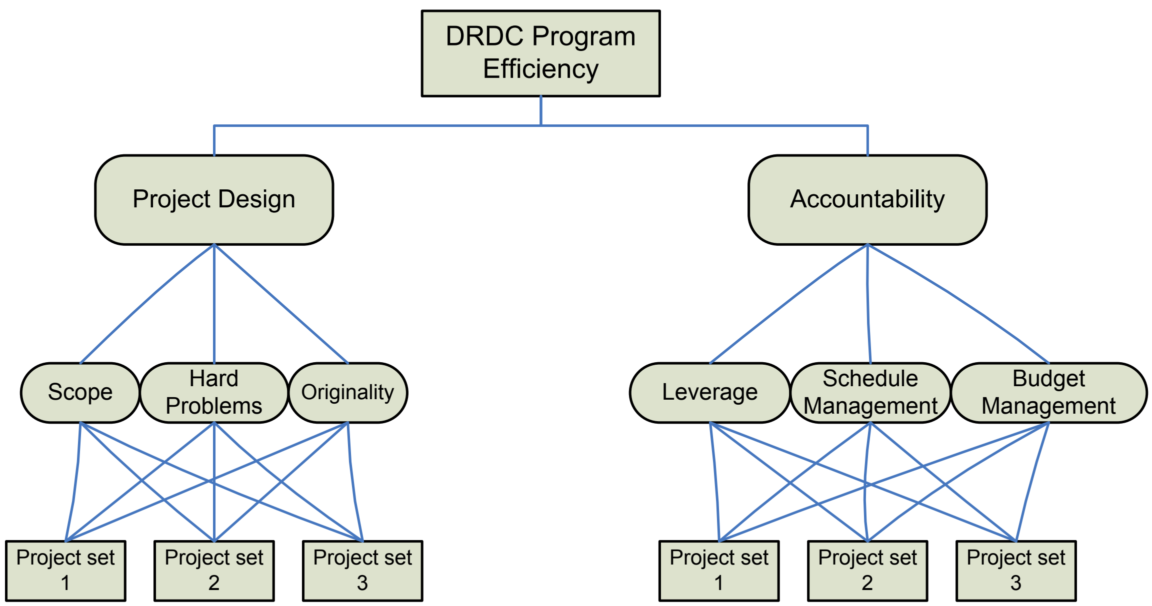


Figure 1. An example of the hierarchical structure of the AHP method based on the DRDC problem

There are two ways of building the hierarchy. The top-down approach is usually implemented when dealing with strategic decisions where the objectives are better defined than the alternatives. The bottom-up approach is used when alternatives are better understood than objectives (Davies, 2001). This is discussed further in the Chapter 3, Methodology.

AHP Hierarchy

The following summarize the steps taken in AHP for a single decision maker (Schmoldt et al., 2001):

1-Model the problem as a hierarchy containing the goal on top, with the subsequent levels containing the main goal decomposed into its criteria and sub-criteria. The alternatives are placed at the bottom of the hierarchy.

2- A pairwise comparison between each of the criteria, and each of the subcriteria at each level is made using a Likert scale.

3- Next synthesizing these pairwise comparison judgments yields a set of overall weights for the criteria and subcriteria by level.

4- Obtain scores for different alternatives with regard to the main objective by utilizing the weights calculated from the pairwise comparisons in step 3.

5-Perform sensitivity analysis to determine how robust the decision ranking is with regard to small fluctuations in comparisons and weights.

In steps 2 and 3 above, weights are calculated for the criteria and the alternatives with respect to each criterion immediately above them. The rankings in terms of individual criteria are then aggregated, giving a final relative score to each alternative. Steps 4 and 5 include calculations which are generally left to computers to carry out (Goodwin and Wright, 2004).

The pairwise comparison is achieved through the decision makers' feedback using a Likert scale based ranking system. The magnitude of preference (of one criterion over another, or one subcriterion over another) is assigned by the decision maker using a number between 1 and 9 as displayed in Table 1 below (Coyle, 2004). The intermediate values are used when more accuracy can be applied to indicate the pairwise preference differences, e.g., in comparing quantitative or continuous scaled values. These values are placed in the decision matrices. For example, if alternative A is "absolutely more important" than B with respect to a particular subcriterion, a +9 is provided as input for this element.

Table 1. The AHP Rating Scale (Coyle, 2004)

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favour one over the other
5	Much more important	Experience and judgment strongly favour one over the other.
7	Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

Consider that Table 2 contains the pairwise comparison for criteria 'Project Design' provided by a decision maker in the hierarchy for the DRDC problem shown in Figure 1 above. An integer value indicates that the item in the row is more important than the one in the column, and a fractional value means the column item is more important that its row. Only the upper triangle of the square comparison table is filled in, since each pair need only be compared once. In Table 2, the decision maker entered $1/3$ to indicate that 'Originality' is 'somewhat more important' than 'Hard Problems'. The value of ½ is entered to indicate that 'Originality' is a little more important (less than 'somewhat') than 'Scope'.

Table 2. Pairwise comparison matrix for criterion 'Project Design'

Project Design	Scope	Hard Problems	Originality
Scope		2	$1/2$
Hard Problems			$1/3$
Originality			

A table similar to Table 2, matrix A, is filled out for each level of the AHP hierarchy. Table 2 is converted to a decision matrix as shown below. Each element a_{ij}, in the below matrix represents the importance value of i^{th} criterion with respect to j^{th} criterion (or alternative i^{th} with respect to alternative j^{th}) at the same level in the hierarchy. A "1" is set for each a_{ii} because it refers to the importance of an alternative compared to itself.

$$A = \begin{bmatrix} 1 & 2 & \frac{1}{2} \\ \frac{1}{2} & 1 & \frac{1}{3} \\ 2 & 3 & 1 \end{bmatrix}$$

The following are observed in the above matrix:

$$a_{ij} = 1, \text{ if } i = j$$
$$a_{ij} = 1/a_{ji}$$
$$a_{ij} > 0$$

In the next step, the principal eigenvector of priorities for matrix *A* is computed (Saaty, 1980):

$$\text{Principal eigenvector } (A) = \begin{bmatrix} 0.466 \\ 0.256 \\ 0.849 \end{bmatrix}$$

Normalizing the above principal eigenvector results in the priority of the subcriteria with respect to the criteria above them, ‘Project Design’.

$$\text{Priority vector} = \begin{bmatrix} 0.297 \\ 0.163 \\ 0.540 \end{bmatrix}$$

The matrix above implies that in the example of Table 2, ‘Originality’ is the most important of the three, followed by ‘Scope’ and ‘Hard Problems’ with their pertinent weights. This procedure is repeated for all branches resulting in local priorities within each branch. The next step consists of multiplying the weights of all nodes all the way to the main objective to obtain the global weight of each criterion at the bottom level.

The best alternative is found through the following formula where a_{ij} represents the relative value of alternative i in terms of criterion j. The weight of criterion j with respect to the main objective is w_j.

$$\text{Best solution} = \max_i \sum_{j=1}^{n} a_{ij} w_j \qquad \text{for } i=1,\ldots,m$$

Consistency

AHP also offers a method to check the consistency of the pairwise comparison input. This is accomplished through the transitivity property:

$$\text{If } (A > B \text{ and } B > C) \text{ then } A > C$$

This means that if *A* is preferred over *B*, and *B* is preferred over *C*, then *A* must be preferred over *C* as well. Furthermore, if *A* is twice as important as *B*, and *B* is twice as important as *C*, then *A* must be four times as important as *C*. Mathematically, this is accomplished through the eigenvalues of the comparison matrices, in which the largest eigenvalue of a consistent reciprocal matrix (λ_{max}) is calculated. Saaty has proved that λ_{max} is equal to the matrix size will establish the matrix's consistency (Saaty, 1980). To present this concept the following factor *CI* is computed:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

CI stands for Consistency Index and *n* is the matrix size (i.e., number of criteria or subcriteria). Furthermore, the Consistency Ratio (*CR*) is calculated by the following formula:

$$CR = \frac{CI}{RI}$$

where *RI* is the average consistency index of a randomly generated sample of 500 matrices, shown in Table 3. Saaty (1980) argues that a value of *CR* less than 0.1 is deemed acceptable. If the consistency is deemed unacceptable, repeating and improving the judgements can produce more consistent results. However minimizing *CR* should not be the focus of the process because flawed comparisons can be perfectly consistent, but will not produce the best decision (Goodwin and Wright, 2004).

Table 3. Average random consistency, RI (Source: Saaty, 1980)

Matrix size	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Average RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

In the example above, the pertinent principal eigenvalue of the matrix *A* is calculated to be λ_{max}=3.009, resulting in a value of 4.5×10^{-3} for *CI*. For a matrix size of *n*=3, RI is estimated at 0.58. Therefore *CR* is found to be *CI/RI*=0.001 (CR<0.1) which indicates high consistency in the pairwise comparison by the participant.

An advantage of AHP is its capability to handle both quantitative and qualitative data in the decision making process. Also a large quantity of criteria can be structured in a practical and manageable way (Mahmoodzadeh et al., 2007). Moreover, the pairwise comparison allows the decision maker to concentrate on only two items at a time.

Critique of AHP

Among objections to AHP, rank reversal is the most critical. It is accepted that through decision making processes, once a new alternative is introduced to a decision problem, the ranking of the previous alternatives should not be disturbed. Rank reversal occurs in situations using AHP in the presence of newly introduced alternatives. However, the validity of this assumption can be disputed in real life scenarios. It is expected that sometimes adding new alternatives can cause rank reversal (Triantaphyllou, 2000).

Saaty himself rejects the idea that rank reversal is a problem with AHP. He argues that the rankings of alternatives are dependent on the rankings of the criteria that depend on the measurements of alternatives. So, the overall ranking of any alternative depends on the measurement and number of all alternatives. To prevent rank reversal then, the priorities of the criteria should not depend on the measurements of the alternatives, but from their own functional importance with respect to higher goals (Saaty, 2001).

DND researchers have been sceptical of AHP and critical of its theoretical assumptions (Edmond, 2006 and Warren, 2004). They argue that the basis for the ranking in pairwise comparison with strength of preference is meaningless. Warren (2004) indicates that the strength of preference displayed in Table 1, is not the same for different individuals. Edmond (2006) believes that the only reliable measure of preference is the actual choice made between alternatives, and it is difficult to understand the relative importance without knowing what contributions the subcriteria make.

The pairwise comparisons can become an obstacle if the number of criteria increases. The number of pairwise comparison required between *n* alternatives is $\sum_{i=1}^{n-1} i = \frac{n(n-1)}{2}$.
Therefore, if the hierarchy is not designed well and has too many elements in one branch, the pairwise comparison becomes a tedious process for the decision makers who would lose interest in the method.

2.3.4 ELECTRE

ELECTRE (ELimination Et Choix Traduisant la REalité, which translates to Elimination and Choice Translating Reality), first introduced around 1966. The main idea behind the method is to deal with outranking relations by applying pairwise comparisons among alternatives under each criteria separately (Triantaphyllou, 2000). ELECTRE has evolved throughout a series of various versions (I, II, III, IV and TRI); however all are based on the same fundamental notion yet are operationally different to address diverse requirements. For example, ELECTRE TRI is designed for assignment problems (Buchanan and Sheppard, 1999).

The concept of "outranking relationship" (denoted as $A_i \rightarrow A_j$) occurs when although the i^{th} alternative is not deemed better than j^{th} alternative quantitatively, it can be taken as a better choice over A_j by the decision maker (Mohammadi et al., 2011).

The structure of the ELECTRE method can be demonstrated through the following seven steps (Triantaphyllou et al., 1998 and Wardoyo et al., 2012):

Step 1. Normalizing the decision matrix:
This method starts with normalizing the decision matrix. The goal of normalization is to make the entries dimensionless. This procedure transforms the decision matrix into a new dimensionless matrix by the following equation:

$$X_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}^2}}$$

Step 2. Weighting the normalized decision matrix:
In this step, the matrix X is multiplied by the vector $W = [w_1, \ldots, w_n]$, where W holds the weight of importance of the corresponding decision criteria.

Step 3. Determining the concordance and discordance sets:
A concordance set of two alternatives is defined as the set of all criteria for which A_k is preferred to A_l:

$$c_{kl} = \{j, \text{ s.t. } y_{kj} \geq y_{lj}\}, \text{ for } j=1, 2, 3, \ldots, n$$

The complementary subset is called the discordance set:

$$d_{kl} = \{j, \text{ s.t. } y_{kj} < y_{lj}\}, \text{ for } j=1, 2, 3, \ldots, n$$

Step 4. Constructing the concordance and discordance matrices:
The concordance matrix represents the degree by which a certain alternative is better than another. The values in the matrix are the sum of the weights associated with the criteria containing the concordance set:

$$C_{kl} = \sum_{j \varepsilon C_{kl}} w_j \text{ , for } j=1, 2, 3, \ldots, n$$

The discordance matrix displays the degree that an alternative is worse than another alternative and its computation is more complex:

$$D_{kl} = \frac{\max_{j \varepsilon D_{kl}} \left| y_{kj} - y_{lj} \right|}{\max_{j} \left| y_{kj} - y_{lj} \right|}$$

It is evident that the elements of the D matrix are not defined when $k=l$.

Step 5. Determining the concordance and discordance dominance matrices:
Concordance and discordance dominance matrices are the products which are constructed by means of a threshold value: alternative A_k will dominate A_l if its concordance index exceeds a threshold. The concordance/discordance matrices have binary entries defined as follows:

Concordance matrix F:

$$f_{kl}=1, \text{ if } c_{kl} \geq c \text{ (threshold)}$$
$$f_{kl}=0, \text{ otherwise}$$

Similarly, discordance matrix G is built from:

$$g_{kl}=1, \text{ if } d_{kl} \geq d \text{ (threshold)}$$
$$g_{kl}=0, \text{ otherwise}$$

Step 6. Determining the aggregate dominance matrix:
The next stage involves determining the aggregate dominance matrix by the cross-product:

$$e_{kl} = f_{kl} \times g_{kl}$$

Step 7. Eliminating the less favourable alternative:
Now using matrix E, if $e_{kl}=1$, then it means that A_k is better than A_l and so on. All columns in matrix E with at least one entry equal to 1 are dominated by the corresponding row. Hence we can eliminate these columns. By eliminating the less favourable alternatives, the best alternative is the one that dominates all others.

This method might yield to multiple alternatives remaining at the end with ranking that might not be unique. It will help eliminate alternatives, but does not necessarily select a champion (Tayebi, 2010). ELECTRE produces a core of leading alternatives by eliminating less favourable ones. It is practical especially when working with few criteria and a large number of alternatives (Triantaphyllou et al., 1998)

This method can be of interest concerning our problem with DRDC since we are selecting a group of R&D projects in a pool of candidates and would not need one ultimate alternative. Therefore, ELECTRE is practical if the alternatives in this thesis are the projects themselves (i.e., more than 400 projects as alternatives).

2.3.5 GRIP

GRIP (Generalized Regression with Intensities of Preference) is an MCDM method for ranking a finite set of alternatives. Just like AHP, GRIP requires the decision maker to provide pairwise comparison between all criteria and alternatives (Slowinski, 2010). However the decision maker is only asked to provide comparison of criteria for the ones that are adequately certain. Figueira et al. (2009) believe that this is an important advantage comparing to AHP method, which requires comparison of all possible pairs of actions on all the considered criteria.

Figueira et al. (2009) state that preference information is one of the motivations behind developing the GRIP method. There is a need of processing information related to strength of preferences. Often, decision makers are willing to provide more information than just a partial order on a set of alternatives/criteria. Thus, it is common to observe statements such as ‘‘Project 1 is preferred to Project 2, at least as much as Project 3 is preferred to Project 4”, expressed on particular criteria and/or on all criteria.

GRIP uses a general additive value function to represent preferences whereas most other MCDM methods work with a single and less general value function (i.e., weighted sum). GRIP decision support process is composed of five main steps (Zielniewicz et al. 2008):

<u>1-Inputting data:</u>
The set of criteria and alternatives are created.

<u>2-Preference information:</u>
The decision maker provides the preference information which can be a partial order on alternatives, which is composed of pairwise comparisons of alternatives, and/or partial preference information on intensities of preferences for some pairs of alternatives.

<u>3-Representing preference information:</u>
The preference information is presented as linear constraints.

<u>4-Computations:</u>
The existence of at least one value function compatible with the preference information is investigated. If none exists, then the decision maker can revise the pairwise comparisons in order to obtain results.

<u>5-Output:</u>
The set of “necessary” preference and “possible” preference relations on the set of all alternatives are produced, which refer to “certain” or “conceivable” preferences respectively.

The GRIP methodology is also implemented in a software package. The GRIP software is written in the Java language as a plug-in to the Decision-Deck platform (Decision Deck, 2013). It uses GNU Linear Programming Kit (GNU Project, 2013) solver to determine the accuracy of preference relations. Zielniewicz et al. (2008) demonstrates an example in the GRIP software's GUI.

The benefits of applying GRIP emerge once additional information about the relation between criteria is available, as discussed above. Also it becomes attractive when some decision makers only have expertise in certain aspects of the criteria.

2.3.6 MARCUS

MARCUS (Multi-criteria Analysis and Ranking Consensus Unified System) is a computer program written in the FORTRAN language using a branch and bound algorithm. This program was developed at Centre for Operational Research and Analysis (CORA) a section of DRDC. The branch and bound algorithm (Land and Doig, 1960) utilized in MARCUS is generally used to examine discrete optimization problems.

MARCUS provides a fast decision support tool involving ranking data in problems that occur frequently in order to reach group consensus. The mathematical logic behind the program is extensively explained by Edmond (2006). It is based on a solution concept that finds a consensus ranking with maximum correlation with the input rankings (Edmond, 2006). The rank correlation is based on a variation of Maurice Kendall's (1938) *tau* (τ) correlation coefficient.

At the user level, the input rankings are entered as integer values. For example, given 4 DRDC projects named 10aa, 10ab, 10ac, and 10ad, a user enters (3,2,1,4) to indicate that 10ac is ranked first followed by 10ab, followed by 10aa, leaving 10ad to the last. The program permits specifying strong ties (entered as 1,2,3,1), and weak ties are specified by negative values (-1,2,3,-1). MARCUS also allows users to not rank an object (entered as 0).

The goal of MARCUS is to acquire fast computation for the size of the problems scientists were dealing with at CORA. It was determined that searching the set of all objects for an optimal solution becomes too time-consuming when the total number of alternatives reaches the range of 15 to 20 projects (Edmond, 2006).

The output of MARCUS consists of up to 100 ranking solutions. If more than one solution is presented, the set of solutions can be used to run the program several times in order to output a single consensus ranking. It also provides a sensitivity analysis displaying the relative strength of consensus of the alternatives in the solution ranking.

Other programs were developed to further enhance MARCUS. BREAKS relies on the concept that it is sometimes advantageous to partition the problem into smaller-sized problems. SLICE, which is another program using MARCUS's algorithm, accomplishes faster response-time by first taking 11 objects and establishing the ranking. Then the 12th option is added to the list and the first 11 of the second round are further processed by the 13th, until all options are exhausted. Finally the remaining 11 are processed until a stable solution is found (Edmond, 2006).

The problem with strategic program prioritization at DRDC deals with around 30 alternatives. MARCUS is limited in handling such volume of data. Although the solution concept in MARCUS is widely acceptable and deemed reliable by the decision makers in DND, it lacks a user-friendly interface and training required to utilize it. It also lacks real-time sensitivity analysis as offered by other MCDM software packages in the market such as the *Expert Choice* (2011), the software that applies the AHP methodology.

2.4 Summary

Considering the advantages and disadvantages of all the methods presented in literature review along with their applications, it is concluded that both MCDM (AHP) and LP can contribute to this particular problem of strategic program prioritization at DRDC.

This optimization problem consists of many well-defined objective functions and criteria. This fact makes the AHP method a good candidate to tackle the problem. AHP's simplicity in implementation of the model makes it attractive. Users obtain a better understanding of objectives by the hierarchy structure and the exercise to construct it. Assuming that there are no interdependencies among the elements in the hierarchy, AHP can be applied to the DRDC problem. When interdependencies exist between elements, Saaty proposes applying the Analytic Network Process (ANP), which is a general case of AHP (Saaty and Vargas, 2006). AHP also takes advantage of the invaluable expertise that exists within DRDC with regard to the structure of the problem. Another advantage of using AHP is the availability of software *Expert Choice* (Expert Choice, 2011) that has automated many steps of AHP algorithm and accommodates sensitivity analysis and various other tools to further investigate the solution.

As for the AHP's rank reversal and rating-scale type, they are of no significance in the DRDC problem of interest to this thesis. Most of these objections are deemed important in theoretical work but would not be crucial for strategic program prioritization at DRDC.

The second MCDM method investigated is ELECTRE. Its approach is to eliminate alternatives to produce a selection that rank higher. This method will help eliminate alternatives, but does not necessarily select a champion (Tayebi, 2010). Moreover, ELECTRE is more practical in cases where quite a large number of alternatives are present and eliminating less favourable alternatives is desired. Therefore AHP is deemed to be a better choice as DRDC would like to manage the program prioritization at the Thrust level, and not the individual projects. This will reduce the number of alternatives to thirty. AHP is also selected over ELECTRE for its ability to always produce a set of ranked alternatives.

The third MCDM method in the literature review is GRIP. This method introduces additional ways to collect a decision maker's input with respect to pairwise comparisons. A decision maker can state whether the preference of a criteria/alternative over another, is at least as much as the preference between a different pair of alternatives. The benefits of applying GRIP can be observed once additional information about the relation between criteria is available. Due to the limited number of criteria in this thesis and lack of availability of such additional preference relations, GRIP is not selected as a decision making tool in this thesis.

The forth MCDM solution that was investigated in literature review is MARCUS. Since this software has been utilized in DRDC and users have gained confidence in its capabilities, it was deemed beneficial to investigate its application in this thesis.

However, despite its advantages, MARCUS does not work best when the number of alternatives surpasses 15 items (Edmond, 2006). The alternatives in DRDC problem are well in excess of this limit, making AHP preferable to MARCUS.

Linear Programming (LP) is also a suitable candidate for our problem. Although our problem tends to be multi-objective, LP can be applied to blend various objectives into one formula by assigning pertinent weights. As discussed, LP has great application in cost-benefit analysis in various fields of study. The challenge in utilizing LP in DRDC problem is determining the benefit function. The projects in DRDC do not yield direct financial gains as they do in the case of most projects in industry. Therefore quantifying the outcome of successful projects in order to measure their benefit is an interesting notion to explore. With AHP being selected as the main driver for this thesis, LP will be utilized as a benchmark. Its results will be compared to AHP's to evaluate the performance of each.

This thesis will contribute to further determination of the adaptability of the AHP algorithm to strategic program prioritization for DRDC.

3 Methodology

This chapter describes how the research is applied and the tools are utilized in order to structure the program prioritization. The MCDM and LP methodologies are selected to be applied to this thesis problem.

The first section discusses details of the DRDC program including general notation of the problem elements for further analysis. Then a model is developed for the DRDC S&T program in LP framework. From this model, it is feasible to determine a set of measurements for performance and effectiveness. These measures are fed to the optimization (LP) algorithm to output the best possible resource allocation. An Excel add-in, *What's Best!* (Lindo Systems, 2011) is used to solve the LP formulation.

The next step consists of developing a model in the MCDM environment using AHP and producing weighted ranking in order to determine the relative importance of each Thrust. Software *Expert Choice* (Expert Choice, 2011) is used to compute the rankings of the alternatives. The AHP pairwise comparisons are conducted by three experts as multiple participants from DRDC that are familiar and involved with the processes in DRDC's S&T program. The feedback from the participants are collected through paper questionnaire and manually inputted into *Expert Choice*'s Group decision making option, and consolidated into a joint ranking.

This chapter starts with section 3.1, "Current Process at DRDC for Program Evaluation", were the existing methods for evaluating S&T projects at DRDC is presented. Also important elements and notations are introduced that will be later utilized and applied. Section 3.2, "Research Process", presents the step-by-step methodology of this thesis. Section 3.3, "LP Problem Formulation", discusses the LP model. Section 3.4, "AHP Problem Formulation", walks through the steps to set up the problem in AHP framework.

3.1 Current Process at DRDC for Program Evaluation

DRDC keeps track of the status of its many projects through a database called Collaborative Planning and Management Environment (CPME). The start and end date of each project along with information on budget and human resource allocations are recorded. CPME also contains the scores of each project with respect to various criteria deemed critical by the management. The management is responsible for keeping CPME up-to-date.

The projects are individually scored on a set of criteria that are deemed critical in the S&T program. Table 4 lists the criteria against which the projects are scored. The scoring scheme is based on simple Likert scale scores of 0 to 5. Scores for projects are provided on an annual basis for the annual allocation process. A score of zero indicates that the project has no relevance to the criteria, whereas 5 show full compliance. Numbers between 0 and 5 are used to indicate the degree of fulfillment of the projects in the particular criteria. (There is one criterion exception to the 0-5 scoring system: the "Exploitation Plan" is scored as a Yes/No to indicate presence or absence of the plan for the project in question.)

Table 4. Categories of Project scores provided in the CPME at the project level (Source: DRDC, 2011b).

	Categories of scores provided in CPME
1	Alignment to Hard Problems
2	Project Originality
3	Exploitation Plan
4	Potential for uptake of deliverable
5	Leverage
6	Project Scope
7	Efficient Schedule Management
8	Efficient Budget Management
9	Quality Evaluation

The scoring is carried out by the DRDC Directors at the Corporate Headquarters who are the points of contact for the Partner Groups to DND and the CF. These scores are determined subjectively to indicate how well a project is doing from the perspective of the Directors. Table 5 displays a portion of the data extracted from CPME along with some project scores. For example, Project 12 is assigned a score of "1" for the element "Potential for Uptake" to indicate the Directors' view that this project is not linked to other existing or future work. Project 2 is highly rated with no data element scores less than 4; Project 19, on the other hand, has no scores greater than 3.

However, this information is not always complete. Some scores are missing, and complete project information is not always available, e.g., Budget Management for Project 9 in Table 5. New projects that have been initiated in the current fiscal year do not contain any scores since they have not yet been evaluated. Other project related information may be missing or incomplete such as start/end date of each project and budget and human resource allocation information.

DRDC has not established a solid association between these scores and the annual resource allocation exercise. Individual managers and Directors review the scores in order to obtain an overview of how well the projects are performing. However, this information influences their final decision in resource distribution.

Table 5. Partial data from CPME (Source: DRDC, 2011b)

Project	Start	End	Alignment - Hard Problems	Project Originality	Exploitation Plan	Potential for uptake	Leverage DST Rating	Project Scope	Schedule Management	Budget Management	Quality DST Evaluation
Project1	**01/04/2008**	**31/03/2013**	5	4	No	3	3	5	5	5	5
Project2	**01/04/2008**	**31/03/2011**	4	4	Yes	5	5	4	4	5	4
Project3	**01/04/2008**	**31/03/2011**	4	4	No	4	3	4	4	5	5
Project4	**01/04/2008**	**31/03/2012**	5	3	No	3	4	5	3	5	3
Project5	**01/04/2008**	**31/03/2013**	5	5	Yes	3	4	4	3	5	4
Project6	**01/04/2008**	**31/03/2012**	4	3	No	3	3	3	3	5	3
Project7	**01/04/2009**	**31/03/2012**	4	4	Yes	4	3	5	3	5	4
Project8	**01/04/2009**	**31/03/2012**	4	3	No	3	3	1	1	5	2
Project9	**01/04/2009**	**31/03/2012**	5	4	No	2	3	3	1		3
Project10	**01/04/2008**	**31/03/2013**	5	3	Yes	4	4	4	4	5	4
Project11	**01/04/2008**	**31/03/2013**	3	3	Yes	5	4	4	4	5	4
Project12	**01/04/2008**	**31/03/2012**	4	4	No	1	3	5	2	5	3
Project13	**01/04/2008**	**31/03/2012**	4	5	No	2	3	5	3	5	4
Project14	**01/04/2008**	**31/03/2011**	3	3	Yes	3	1	5	3	5	3
Project15	**01/04/2008**	**31/03/2015**	4	5	Yes	5	3	4	4	4	5
Project16	**01/04/2008**	**31/03/2013**	5	4	No	4	4	4	4	5	5
Project17	**01/04/2008**	**31/03/2015**	4	4	No	4	3	4	4	4	4
Project18	**01/04/2008**	**31/03/2013**	3	4	No	3	4	3	3	4	3
Project19	**01/04/2007**	**31/03/2010**	2	2	No	2	3	1	1	1	2

3.2 Research Process

The outcome of this research provides a mechanism to improve the assignment of budget and human resources (with various skills) to Thrusts. It helps decision makers to address inadequate progress in certain areas that are deemed critical and reinforce satisfactory progress in others. The process is divided into steps as follows:

1) Problem description – present details of DRDC problem including general notation of the problem elements for further analysis;
2) Problem formulation – prepare alternative problem formulations of the DRDC problem for (i) single-valued objective LP optimization; and (ii) multiple objective AHP formulation for alternative allocation, evaluation and ranking;
3) Problem solution – solve the modelled problems: (i) solve the LP optimization allocation as a benchmark; (ii) solve the AHP problem;
4) Comparison and Sensitivity – compare the benchmark LP and AHP solutions to the current problem resolution and evaluate the results;
5) Summary and Conclusions – given the comparative analysis results, recommend an improved procedure for structuring DRDC's S&T annual program evaluation.

The first step in the research process is to provide a detailed description of the actual DRDC process and results. This description is important for comparing the modelled approaches as methods for future allocations. Once the actual process is well-detailed, then the procedure allows for a more reliable model for the next step of the process.

The second step formulates the problem using the relevant mathematical notation following from the descriptive elements for the proposed models (LP and AHP).

The two research process allocation formulations are presented in parallel: (1) the LP optimization formulation sets up the problem of the resource assignment with respect to Thrusts, and (2) the AHP multiple criteria formulation is used to rank alternative groups of Thrusts.

Figure 2 below describes the proposed method to conduct this research:

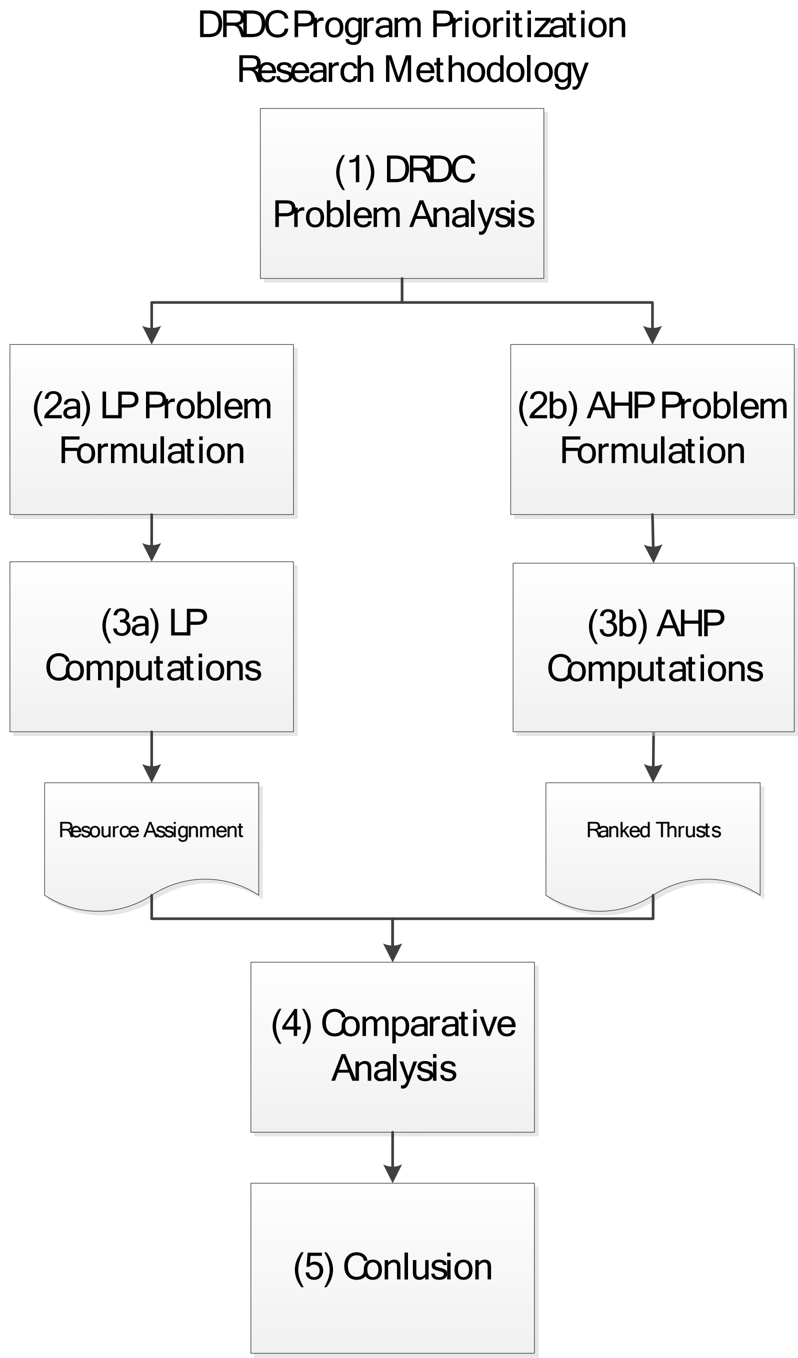


Figure 2. Research Process, high-level flowchart

The AHP problem is formulated into two phases. This permits the breakdown of the hierarchical complexity with regard to the large quantity of Thrusts. During Phase I, similar Thrusts are grouped together in logically defined groups. Then AHP is applied to rank the Thrusts within each group. This ranking is performed in each group independently. The results of Phase I consist of multiple Thrust groups that have their members ranked.

In Phase II, the Thrusts groups are regrouped. Thrusts with equal rankings from Phase I are put together into new groups. Then the groups are ranked within the same hierarchy as in Phase I with respect to the DRDC goal, which is its program efficiency. The final result consists of ranked groups of (possibly) dissimilar Thrusts. The idea is to ensure that best Thrusts from different backgrounds receive their relative share of resources.

As explained, in parallel to the AHP method, the problem is formulated using Linear Optimization for benchmarking. The outcome of the two approaches will be analyzed to compare the performances of each method against the results from the actual allocation process. The data facilitating our methods are extracted from DRDC's project database which contains specific details of various projects, as described in section 3.1 above. Finally, in Chapter 4, the results of both LP and MCDM methods are analyzed.

3.3 LP Problem Formulation

The LP optimization algorithm distributes resources to the Thrusts in order to maximize the quantified single valued objective function. The results of the LP optimization algorithm are then taken to the PGs as guidelines to quantify the share of resources for each Thrust.

Considering the organizational structure at DND and existence of Thrusts, skill types and human and financial resources, the resource assignments consists of reallocating individuals and distribution of financial resources between Thrusts as necessary.

This section defines the relationship between the parameters of the problem to establish the structure of the DRDC problem for linear optimization. The DRDC problem is a strategic resource assignment, which is not easily quantified nor directly measured through its outcomes.

The main goal for LP in this thesis is to create a benchmark that can be used to compare the results of AHP model and the actual practices.

The DRDC resource allocation optimization is expressed through the following LP formulated problem (For a complete LP formulation process refer to Appendix C – LP Data Elements and Appendix D – LP Formulation Problem):

Let X_{ij} denote the FTE resource assignment in Thrusts i of Type j, and let Y_i denote the budget allocation to Thrust i respectively.

Given C_{ij} and D_i as the pertinent benefit functions such that the objective is to:

$$\text{Maximize} \qquad Z = \sum C_{ij} X_{ij} + \sum D_i Y_i$$

where i is the Thrust index ($i=1, 2, 3, \ldots, 30$) and j is the FTE type index ($j=1, 2, 3, \ldots, 11$).

Subject to:

1) Non-negativity of the resource assignment

$$X_{ij} \geq 0,\ Y_i \geq 0$$

2) Upper bound on total FTEs

$$\sum X_{ij} \leq 640 \text{ FTEs}$$

3) Lower and upper bound of each FTE type assigned to each Thrust

$$FTE\_min_{ij} \leq X_{ij} \leq FTE\_max_{ij}$$

4) Lower and upper bound of total FTE in each Thrust

$$FTE\_Thrust\_min_n \leq \sum X_{in} \leq FTE\_Thrust\_max_n \qquad (1 \leq n \leq 30)$$

5) Upper bound of total FTEs of a certain type

$$\sum X_{im} \leq FTE\_type\_max_m \qquad (1 \leq m \leq 11)$$

6) Upper bound limit on total FTEs of multiple types

$$\sum X_{ij} \leq FTE\_type\_Group1\_max \qquad (1 \leq i \leq 3)$$
$$\sum X_{ij} \leq FTE\_type\_Group2\_max \qquad (4 \leq i \leq 7)$$
$$\sum X_{ij} \leq FTE\_type\_Group3\_max \qquad (8 \leq i \leq 9)$$
$$\sum X_{ij} \leq FTE\_type\_Group4\_max \qquad (10 \leq i \leq 11)$$

7) Upper bound of the total budget

$$\sum Y_i \leq Total\_Budget \text{ (\$34M)}$$

8) Lower and upper bound of fund awarded to each Thrusts

$$Y\_min_i \leq Y_i \leq Y\_max_i \qquad (i=1, 2, 3, \ldots, 30)$$

The above captures the complete LP formulation of the DRDC S&T annual allocation problem in algebraic form. The analysis for the results of the LP solution is provided in the upcoming Chapter 4. The following section presents an alternative formulation for resource allocation, in a multi-criteria decision framework using AHP.

3.4 AHP Problem Formulation

As discussed in the literature review Chapter 2, section 2.3, AHP is based on pairwise comparisons between the criteria and subcriteria at each level of its hierarchy thereby establishing priority among the criteria. By applying AHP to the DRDC's problem, the main objective is decomposed into a hierarchy of more easily comprehensible sub-objectives (subcriteria), each of which contribute to the overall objective and allowing for them to be analyzed independently. This captures the characteristics of the problem from a high-level concept into a disaggregated set of important attributes. Accordingly, the idea behind AHP is to organize the thoughts of decision makers and management with respect to the objectives and structure of the problem.

3.4.1 AHP Hierarchy

The first exercise in solving any problem with AHP is to understand the elements of the system. There are 30 Thrusts that are the problem "alternatives" to which the FTEs and funds are allocated. Considering the fact that there is not a single winner and all Thrusts will benefit from the resources, we are interested in a relative ranking of the Thrusts. This ranking represents the portion of the share (funding and FTEs) to which each Thrust is entitled.

The hierarchy structure of the problem criteria and attributes is based on management's expertise and experience. The criteria may be grouped together in multiple levels in order to detail the important attributes.

Creating the hierarchy structure is an important step in the problem solution with AHP. Through discussions with DRDC, it was determined that the criteria for individual projects as used in CPME for scoring purposes, are appropriate and sufficient for use at the Thrusts level. Figure 3 displays the model that is focused on the Thrust characteristics. The Thrusts are ranked against criteria that are extracted from the CPME. These criteria are approved at the ADM level in DRDC. The top level in the hierarchy worded as the main objective or "Goal" of the problem. The top level is termed "DRDC Program Efficiency".

The criteria are categorised into four groups in order to facilitate easier processing by decision makers. The main criteria (Design, Accountability, Outcome and Overall Quality) are created based on grouping similar scoring criteria from the CPME. The terminologies were selected in consultation with DRDC, in order to make the pairwise comparisons meaningful at the criteria level with respect to the overall goal. The subcriteria are located one level lower. 'Overall Quality' only contains one subcriterion. The Thrusts, which are the alternatives, are placed at the bottom of the hierarchy. The alternatives, subcriteria and the main objective were known and well defined. However, the mentioned items in criteria were defined based on the subcriteria under them. Therefore structuring of the hierarchy has followed a bottom-up approach.

Another benefit of the hierarchy structure is for the decision makers and researchers to review the problem and acquire a better understanding of the relationships between its elements.

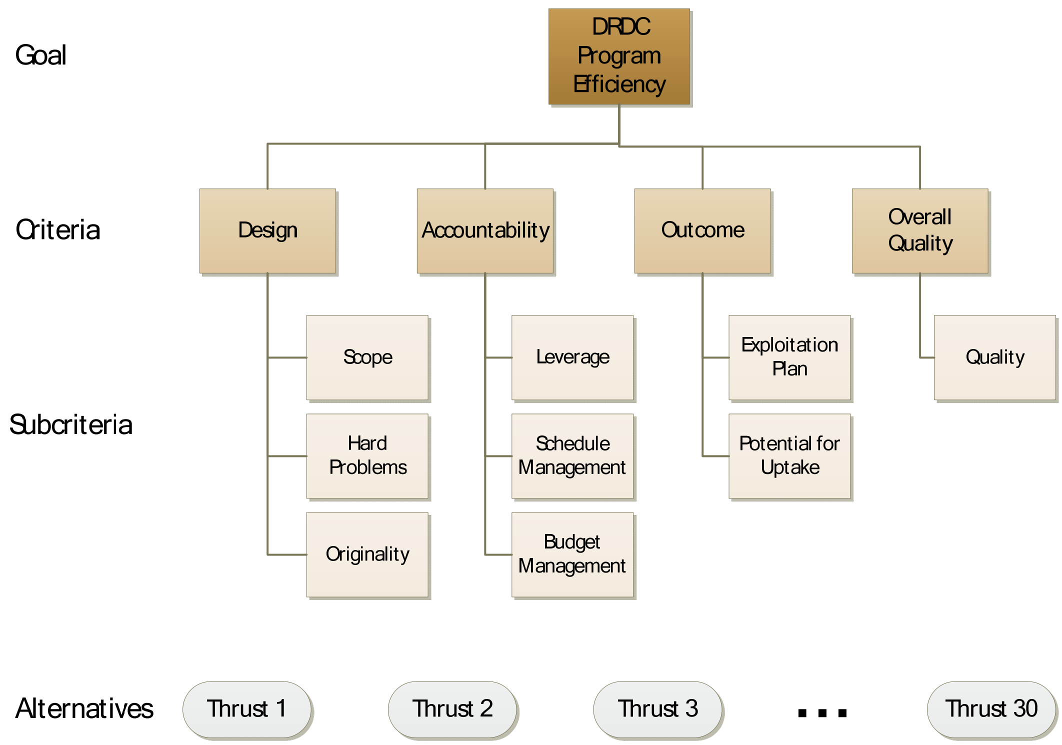


Figure 3. AHP Phase I hierarchy based on subcriteria from CPME

The actual ranking and computation is facilitated by *Expert Choice* (Expert Choice Software, 2011) software developed to help decision makers along the steps of the AHP algorithm. It provides a user-friendly input system and takes care of the calculations in the background so that the decision makers can concentrate on setting up the hierarchy of their problem. The utilization of the computer based software also accommodates easy sensitivity analysis and further inspection of the data and the results. *Expert Choice* also supports inputs from multiple decision makers. The academic version used in this thesis, only allows for a limited quantity of users (5) to take part in the group decision making process.

Figure 4 displays the AHP hierarchy as is set up in the *Expert Choice's* "tree-view". The Graphical User Interface (GUI) in *Expert Choice* provides ease of use for design and manipulation of the hierarchy. The elements can be dragged and dropped into new positions in the structure as required. Branches can be expanded or retracted by the plus/minus sign beside each category for better visual organizations.

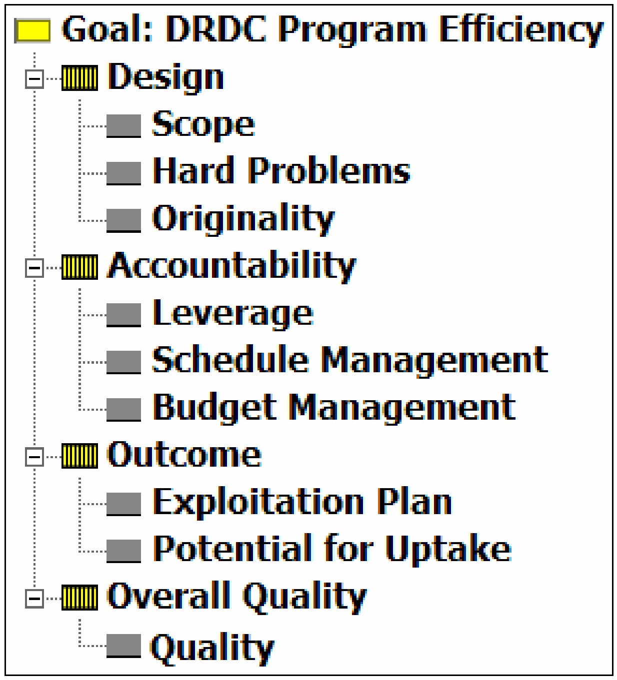


Figure 4. Hierarchy of the Phase I in Expert Choice tree view (Source: Expert Choice, 2011)

Once the hierarchy is established and decision makers have agreed on its validity, pairwise comparisons are required to determine the weights of each element in the hierarchy. Through *Expert Choice*, the pairwise comparisons between elements at each level of hierarchy are entered by decision makers and used to establish trade-off valuation and weights.

The first set of computations involves the ranking of same-level criteria. Pairwise comparison of criteria in each branch with respect to their immediate higher level criteria is performed. Each item obtains a local weight, within its own branch. Expertise of the management is applied to perform the pairwise comparison between the criteria.

Expert Choice provides various means of entering the pairwise comparison. The preferences are recorded in the software by numbers (i.e., Likert scale values 1 to 9 as explained in the literature review section 2.3.3), graphical representations and verbal judgements. *Expert Choice* then translates all the input into a unified scoring scale.

In this research each decision maker has been provided with a questionnaire and instructions on how to provide their pairwise comparison results into tables, as shown in Table 2 (above). The questionnaire is available in Appendix L – Questionnaire for AHP pairwise comparison. The feedback is then manually entered into *Expert Choice* for each of the three participants separately. *Expert Choice* then aggregates the multiple inputs to produce a final weighting for each item in the hierarchy. It is assumed that all decision makers have the same weight in this thesis.

There are two levels of comparisons to be completed. First, the four main (first level) criteria are weighted against the main objective or "Goal". Then the subcriteria within each criterion are weighted with respect to their criteria. *Expert Choice* then synthesizes these inputs into local and global weighting scheme for each criteria and subcriteria. Table 6 displays the weighting of the criteria of the hierarchy computed for each participant. *Expert Choice* also displays the Consistency Ratio (CR). Saaty (1980) considers a CR value of less than 0.1 to be deemed acceptable and implies consistent ranking input by the decision maker. The decision maker can modify its input at anytime to adjust the CR and observe the outcome in the overall or local ranking. However this was not exercised on the pairwise comparisons of the three participants.

Table 6. The weighing of criteria produced by Expert Choice from 3 experts' inputs

Decision Maker	1	2	3	Combined
Name	Participant 1	Participant 2	Participant 3	
Affiliation	DRDC	DRDC	DRDC	
Expertise	Program Management Human factors research	Program Management Human factors research	Program Management Human factors research	
Weight computed to 'Design'	0.213	0.148	0.055	0.134
Weight computed to 'Accountability'	0.060	0.203	0.118	0.120
Weight computed to 'Outcome'	0.426	0.194	0.565	0.387
Weight computed to 'Overall Quality'	0.301	0.455	0.262	0.359
Consistency Ratio	0.05	0.17	0.04	0.01

The second step involves the pairwise comparison of subcriteria. Again, the experts are asked to provide their preferences in *Expert Choice* with respect to the subcriteria located under each main criterion. The users once again have the verbal, graphical and numerical methods to work with. The decision makers may use any of these comparative methods to provide their pairwise comparison results. They can also use a different method of comparison independent of the previous choices they have made. Table 7 display the weighting of hierarchy subcriteria computed by *Expert Choice* using the participants' input. The weighting in this table is provided at local and global levels. Local refers to the weighting of the subcriteria with respect to the criteria just above it. Global value refers to the weighting of the subcriteria with respect to the main goal.

There are three different ways to incorporate the input from the three participants in this problem. One approach is aggregating the individual judgements into a single decision representing the group. The second is the aggregation of the individual preferences per criterion. The third is to select a group choice from individual choices. Some expert decision makers tend to prefer to aggregate their final outcomes from their hierarchy and not from their judgements (Pedrycz et al., 2011). *Expert Choice* utilizes the geometric mean to obtain a group average for the judgements before computing the weights for criteria. Saaty (2008) explains that the synthesis of the reciprocal of judgements must be equal to the reciprocal of the synthesised judgements. Therefore only geometric mean can be applied to accomplish the synthesis and not the widely used arithmetic mean.

Table 7. The weighting of subcriteria produced by Expert Choice from expert input

Decision Maker	1		2		3		Combined	
Name	Participant 1		Participant 2		Participant 3			
Affiliation	DRDC		DRDC		DRDC			
Expertise	-Program Management -Human factors research		-Program Management -Human factors research		-Program Management -Human factors research			
	Local	Global	Local	Global	Local	Global	Local	Global
Criteria: Design								
Weight computed to 'Scope'	0.464	0.099	0.076	0.011	0.202	0.011	0.218	0.029
Weight computed to 'Hard Problems'	0.281	0.060	0.766	0.113	0.701	0.039	0.603	0.081
Weight computed to 'Originality	0.255	0.054	0.158	0.023	0.097	0.005	0.179	0.024
Consistency Ratio	0.35		0.13		0.13		0.04	
Criteria: Accountability								
Weight computed to 'Leverage'	0.754	0.045	0.172	0.035	0.258	0.030	0.425	0.051
Weight computed to 'Schedule Management'	0.181	0.011	0.102	0.021	0.105	0.012	0.164	0.020
Weight computed to 'Budget Management'	0.065	0.004	0.726	0.147	0.637	0.075	0.411	0.049
Consistency Ratio	0.13		0.03		0.04		0.06	
Criteria: Outcome								
Weight computed to 'Exploitation Plan'	0.167	0.071	0.500	0.097	0.833	0.471	0.500	0.193
Weight computed to 'Potential for update'	0.833	0.355	0.500	0.097	0.167	0.094	0.500	0.193
Consistency Ratio	0.00		0.00		0.00		0.00	

In order to facilitate effective ranking, the AHP algorithm is broken down into two phases. During the first phase, Thrusts that are similar and related are placed together in multiple groups. Then the Thrusts within each group are ranked internally. In the second phase, the groups are rearranged so that Thrusts with similar ranking and performance (in Phase I) are put together. Then the Thrust Groups are ranked using AHP in order to compete amongst themselves and determine their relative share. The idea is to award the best performing Thrusts from different backgrounds. In the next section, the steps to group similar Thrusts together are explained.

3.4.2 Clustering Thrusts

Looking back at how DRDC handles its S&T program (Section 3.1), Thrusts are already grouped together under the PGs (Wheaton and Bayly, 2010). Table 8 displays the current record of Thrusts that were utilized for this thesis. Each PG covers 3 to 6 Thrusts. The representation of PGs and Thrusts in this thesis has been modified from the original DRDC protocol.

One way to process Thrusts in smaller numbers is to rank the Thrusts within each Partner Group (PG). After Thrusts within each PGs are ranked, we can then rank the PGs themselves. Finally the outcome from both stages of ranking are processed to result in a global ranking for all Thrusts. Logically, Thrusts within the highest ranked PG are not necessarily ranked highest among other Thrusts. The concern here is how to bring together the results of two phases into a meaningful outcome.

Table 8. Distribution of Thrusts within partner groups (Source: Wheaton and Bayly, 2010)

Partner Group	**Thrusts**
PG1	1, 2, 3
PG2	4, 5, 6, 7, 8, 9
PG3	10, 11, 12, 13, 14, 15,
PG4	16, 17, 18, 19, 20, 21
PG5	22, 23, 24, 25, 26
PG6	27, 28, 29, 30

There are objections by DRDC for ranking PGs. It is deemed bad business practice to rank the PGs directly. It must be considered that, in reality, Thrusts within each PG are not necessarily similar. Hence, grouping Thrusts based on their characteristics to bundle together the ones that have more in common is important. The interrelationships between the thrusts are identified in order to define how Thrusts could be combined together into portfolios. Once Thrusts are categorized in a meaningful way, AHP is used to rank them. This ranking bears more value now that the competing Thrusts in each group have similarities.

In order to group Thrusts based on their characteristics, the k-means clustering algorithm is used. Before attempting to cluster Thrusts, a set of characteristics are determined that can be used to discriminate between them. There are two sets of information that are made available through CPME. These are: (i) scores that are given by management on various criteria; and (ii) the second set contains project information such as allocated budget and quantity of FTEs assigned (as listed in section 3.3.2). Table 9 contains the second set, the project information. The information in Table 9 is used for clustering purposes. This information is extracted from CPME for the fiscal year 2009-2010.

Table 9. Project information elements extracted from CPME for clustering

CPME Thrust information Used for clustering
1. DRDC Funds (dollar value) 2. DND Leveraging (dollar value) 3. Total FTEs (number of individuals) 4. Total FTEs Budget (dollar value) 5. Scientists (number of individuals)

Clustering algorithms

There are various methods used to partition a group of observations into clusters of data. Principal Component Analysis (PCA), Linear Discriminant Analysis (LDA) and k-means are three well-known algorithms that are discussed below.

PCA is one of the methods used for reducing dimensionality of data for further analysis. PCA strives to reduce the variable dimensions while working on similarities between members in each cluster and between clusters themselves. PCA tries to preserve the variance in the high dimensional data as much as possible (Holland, 2008).

LDA's aim is to reduce the many dimensions of the data while retaining as much discriminatory information as possible. LDA's focus is to determine which variables discriminate between data. Usage of LDA requires certain conditions to be met within the data, but it provides better control over the quantity of members in each group. To use LDA the data is assumed to have a Gaussian distribution. Martinez and Kak (2001) have shown that once the data set is small, which is the case in DRDC problem with 30 Thrusts, PCA outperforms LDA.

As mentioned, the population must have a Gaussian distribution in order for LDA to work effectively. In order to investigate this property in the DRDC data, the Shapiro-Wilk test is applied. Shapiro and Wilk (1965) showed that their method is an effective measure of normality even when the sample size is less than twenty. To do the distribution test, the '*R*' software is utilized along its function library for the Shapiro-Wilk test. '*R*' was created by Ross Ihaka and Robert Gentleman at the University of Auckland, New Zealand, and now, '*R*' is developed by the '*R*' Development Core Team.

'*R*' is based on language '*S*' created by John Chambers (R Project, 2012). Table 10 summarizes the test results for the five variables in the data set.

Table 10. Result of Shapiro-Wilk test for Thrust data set

	DRDC Funds	**DND Leveraging**	**Total FTEs**	**Total FTEs Budget**	**Scientists**
W	0.9557	0.7349	0.8808	0.8987	0.9754
p-value	0.2392	5.249×10^{-6}	2.939×10^{-3}	7.826×10^{-3}	0.6949

Considering the values of W and p for DND Leveraging, Total FTEs and Total FTEs Budget, it is determined that they are not normally distributed due to the low p values of Table 10. Appendix J – 'R' Data Components for Clustering, contains the Quantile-Quantile plots and the histograms for the data in Table 10 as well. The point pattern in the Quantile-Quantile plots are not linear for DND Leveraging, Total FTEs and Total FTEs Budget, indicating that they are not normally distributed. The histograms for the DND Leveraging, Total FTEs and Total FTEs Budget is also right skewed and indicates they are not normally distributed (See Appendix J–'R' Data Components for Clustering for histograms and Q-Q plots). Thus, since LDA does not carry out as well when the number of samples is low, then LDA is not selected as a clustering method for the data. The PCA's focus on reducing the dimensionality of the data can potentially make the clustering easier, however the objective of interest is to define more clusters categories than just two. This will ensure that diversity in Thrusts is presented in future calculations. Therefore, it is decided to proceed with k-means for clustering Thrusts.

k-means does not require many pre-conditions or assumptions and is data-driven, however the number of members in each cluster is not as controllable. k-means takes the data and number of desired clusters as its input. It divides the data into k groups and through optimization tries to create more compact clusters that are well separated. k-means minimizes the within-cluster sum of squared distances through iterations (Pollard, 1981 and Wang and Song, 2011).

The following summarizes the steps involved in k-means clustering (Ray and Turi, 2000 and Govaert, 2009):

1. Select the initial cluster centres (means). The number of clusters, k is determined by the decision maker, i.e., the k cluster means are denoted:
$$z_1(1), z_2(1), z_3(1), \ldots, z_k(1)$$

2. Distribute the samples between clusters based on the minimum Euclidean distance, i.e.,

$$x \; \varepsilon \; C_j(k) \;\; \textbf{if} \;\; \|x-z_j(n)\| < \|x-z_i(n)\|$$

where C_j is the cluster which has $z_j(n)$ as its centre.

3. Compute the new cluster centre that minimizes the sum of the squared distances of all points to the new cluster centres, for each cluster. N_j in the following formula is the number of members in each cluster and *n* is the number of iterations performed:

$$z_j(n+1) = \frac{1}{N_j} \sum_{x \in C_j(k)} x \ , \quad j=1,2,\ldots,k$$

4. If, at iteration *n+1* the new cluster centre is identical to the old one (i.e., $z_j(n+1)=z_j(n)$), then the algorithm is terminated (no more improvements are possible). If not, step 3 is revisited and new cluster centres are calculated again.

k-means is sensitive to the initial conditions, which are the randomly-selected means of each cluster (step 1 in above algorithm). Therefore the results of the k-mean algorithm can be slightly different each time it is calculated (Krawetz, 2009).

There are various software packages to help with the statistical calculations. This thesis uses '*R*' to accomplish this task. A function for k-means calculations is already implemented in '*R*' and available in its library. Appendix J – 'R' Data Components for Clustering contains the code the output of the k-means function in '*R*'.

Fitness of clustering algorithms

There exist methods to evaluate the performance of clustering algorithms. Evaluating the results of clustering is done through internal or external methods. The internal methods utilize the quantities and information from the dataset itself. However, external techniques rely on information other than the data itself such as external benchmarks. External methods measure how close the clustering is to the predetermined benchmark classes.

In order to evaluate k-means performance, the Davies–Bouldin index (DBI) which is an internal method of validation (Davies and Bouldin, 1979), is utilized. DBI is defined as the ratio of the within cluster scatter to the between cluster separation. Therefore a lower value means that clustering is better. In the following DBI formula, $\Delta(X_i)$ is the intra-cluster distance (diameter of X_i), $\delta(X_i,X_j)$ is the inter-cluster distance and *k* is the total number of clusters:

$$\text{DBI} = \frac{1}{k} \sum_{i=1}^{k} \max_{j \neq i} \left\{ \frac{\Delta(X_i) + \Delta(X_j)}{\sigma(X_i, X_j)} \right\}$$

Clustering DRDC Thrusts with k-means

A function for k-means algorithm is implemented in software '*R*' and available in its library. Appendix J – 'R' Data Components for Clustering contains the codes in '*R*' in order to implement the data for statistical analysis that is discussed in the remainder of this section.

In order to verify the strength of the clustering, the fitness indicators k-means' output for clusters sizes of 2 to 14 are computed. The k-means algorithm is run 10 times and the DBI, total-within-cluster-sum-of-squares and also separation (ratio of *between-cluster-sum-of-squares* to *total-within-cluster-sum-of-squares*) is displayed as in Figure 5 for multiple cluster sizes. Each time k-means is run, 10,000 different initial conditions are tested and the best result is printed. These initial conditions are random numbers selected by the algorithm as means of clusters.

By k-means, the separation between groups is maximized, while minimizing the distance between members within each cluster. Analyzing the three plots in Figure 5, improved separation values increase with increasing *k*.

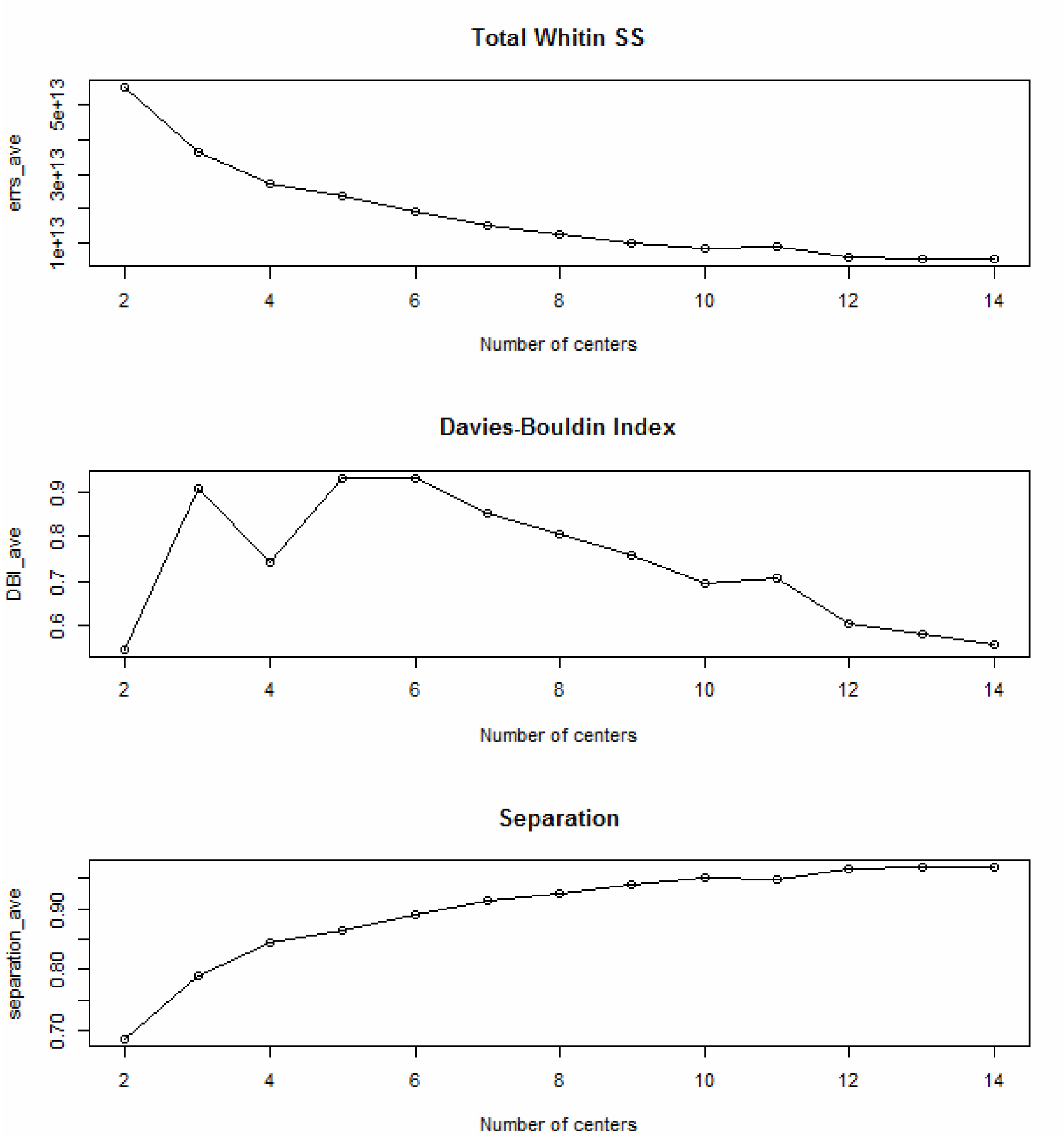


Figure 5. Cluster compactness, DBI index and separation, clusters sizes 2 to 14 (Source: R Software)

It is desirable to divide Thrusts into 5 or 6 clusters with approximately 5 or 6 members in each cluster. This is to accommodate the AHP algorithm for which ranking are more meaningful with fewer items to be ranked. Results of executing the k-means command in '*R*' with value of *k*=5 and 10,000 iterations are displayed in Table 11.

Table 11. Output of k-means algorithm in R for k=5 (Source: R Software)

```
>kmeans(thrusts,5,10000)

K-means clustering with 5 clusters of sizes 11, 5, 6, 5, 3

Cluster means:
       [,1]      [,2]     [,3]    [,4]     [,5]
1  629818.2  162045.5 16.90909 1477224 14.98000
2 1355600.0 1098980.0 38.80000 3372815 22.98600
3 1088083.3  728283.3 13.00000 1165275  7.99000
4 1289800.0 5603422.0 47.80000 4038427 24.11400
5  997000.0 2343111.7 20.33333 1761572 12.11667

Clustering vector:
 [1] 1 1 2 4 3 4 4 1 1 1 2 5 4 5 3 3 4 1 3 5 1 1 1 1 3 2 3 1 2 2

Within cluster sum of squares by cluster:
[1] 4.325614e+12 [2] 3.791009e+12 [3] 1.627102e+12 [4]
1.332875e+13 [5] 1.708611e+12
 (between_SS / total_SS =  85.8 %)
```

The output of Table 11 contains the sizes of each cluster (number of Thrusts in each) as well as the means of each variable in each cluster. The clustering vector indicates the number of the cluster to which each of the 30 Thrusts belongs.

As explained earlier, because of the sensitivity to initial conditions (which are the initial random values selected for each cluster's mean), the output of k-means in each run is not identical. The randomly selected cluster means are different in each iteration. However, it is observed that as the value of k increases, most of the time only the labeling of the clusters are changed and not the means and quantity of members in each cluster. Running the k-means algorithm with more iterations results in improved values and greater cluster separation. A value of 10,000 is selected for the number of iterations in the k-means algorithm. Many tests with higher numbers of iterations did not result in better solutions. Based on the overall results using '*R*', the clustering of Thrusts is shown in Table 12.

Table 12. Clustering of Thrusts by k-means algorithm, k=5

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
1 2 8 9 10 18 21 22 23 24 28	3 11 26 29 30	5 15 16 19 25 27	4 6 7 13 17	12 14 20

In Table 12 above, Cluster 1 is the biggest group with 11 Thrust members. Cluster 5 is the smallest with only 3 Thrust members. The target is to have around 6 Thrusts in each cluster. To this end, a manual arrangement of the k-means' output is proposed based fundamentally on the *k*=5 means clustering of Table 13 which provides a more balanced and intuitive clustering of the Thrusts. Moreover, as discussed and demonstrated in the output of the k-means algorithm in '*R*', each cluster is computed based on the vector of means for each variable. Therefore the quality of each cluster can be worded in terms of variables to explain the reason behind grouping certain Thrusts together and justify the clustering.

In this respect, it is opportune to take advantage of the fact that the data quantity is not high, i.e., separating 30 Thrusts to clusters is not a time consuming computing process in order to refine the output of the k-means algorithm. Certain patterns are observed by inspecting the Thrust variables in each cluster. For example, Cluster 4 is one of the most solid groups with Thrusts that visibly have high DND leveraging which are values of \$3.6M and higher with 3 Thrusts at \$6M. The average for DND leveraging in other clusters is ~\$750K with the highest value being \$2.8M.

Cluster 2 includes some Thrusts with high DRDC funds (more than \$1.3M). Cluster 1 mostly consists of Thrusts that have low DND Leveraging (less than \$270K). Cluster 3 contains Thrusts that have low number of FTEs (less than 10 FTEs). There are some Thrusts scattered that are midrange for both DND leveraging and DRDC fund allocations (with DND Leveraging between \$580K and ~\$1M and DRDC funds between \$350K and ~\$2M in Clusters 1, 2 and 5). With some modifications in Table 12, the clustering can be refined to produce Table 13 which is a more meaningful grouping of Thrusts.

Table 13 provides the refined clustering of the Thrusts based on natural and intuitive definitions. It is noted in Table 14 that the sum of squares increases (relative to strictly determined 5-means clusters), and the DBI value declines in refined versus raw k=5 clusters. However, the separation ratio changes minimally, and based on this, the more intuitive and balance clustering is argued. Each cluster consists of Thrusts that display similarities in the context of at least one variable of Table 9.

Table 13. Refined clustering of Thrusts by manipulating data

Cluster	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**
Data Characteristics	High DND Leverage	High DRDC fund	Low quantity of scientists	Low DND Leverage	Midrange DND Leverage and DRDC fund
Thrust Membership	4 6 7 13 17 20	3 19 25 26 28 30	5 15 16 18 23	1 8 9 10 21 24	2 11 12 14 22 27 29

Table 14 demonstrates a comparison specifically between an output of k-means for k=5 which has been taken from Table 12 (denoted as the raw data) and the refinement that resulted in clusters in Table 13 (denoted as the refined data). Table 14 indicates that the value for the total within cluster sum of squares has increased while the separation has only slightly declined. However, the value of DBI which is the indication of clustering quality demonstrates visible improvement.

Therefore, it is concluded that the refinement of the k-means output for k=5 has not degraded the quality of clusters.

Table 14. Comparative analysis between raw output of k-means and refined clusters for k=5 clusters

Cluster	**Raw data**	**Refined data**	**Difference**
Total within cluster sum of squares	2.47×10^{13}	4.84×10^{13}	+95%
DBI	1.01	0.60	-0.41
Separation ratio (between cluster sum of squares / total sum of squares)	0.85	0.83	-0.02

The Thrusts with similar characteristics are now clustered into five groups as in the refined results of Table 13. In the next section the project scores from CPME are applied in *Expert Choice's* data grid in order to facilitate ranking.

3.4.3 Thrusts' scores and Expert Choice's Data Grid

The AHP Data Grid permits the recording of the scores for each of the candidate Thrusts to be ranked. The Thrusts scores are then applied to the AHP problem weighted hierarchy for comparative analysis and ranking. As for the LP model (of section 3.3), the Thrust scores are either the arithmetic mean or the median of project scores within each Thrust.

The scoring system is input to the data grid along with the utility function that further explains the true meaning of score values. The utility function permits DRDC decision makers to acknowledge the trade-offs and desirable versus undesirable levels of the data scores. For example, depending on the score element, the recorded low end scores of 1, 2, or 3 may be judged to be relatively indifferent, whereas scores of 4 or 5 may indicate a difference greater than the simple number scale ordinal measure. The dimensionless utility function permits the capture of decision makers' interpretation without scale or differences in unit measurement of scores, e.g., dollar values versus Likert scale 1-5 values. For the DRDC data, these trade-offs and interpretations are based on the overall recorded data to Thrusts for each data element as described below. The criteria in the DRDC problem demands an increasing utility function because scores and the higher they are, then the more intrinsic value they have to decision makers.

Density functions and the pertinent utility functions for the score categories are discussed in the following pages. The utility functions are designed to capture the portion of the scores with higher relative frequency thereby reflecting the decision makers' interpretative scoring system.

The utility function for “Hard Problems” can be defined as follows in Figure 6 to cover the range of data from 2 to 5 as provided for this data element.

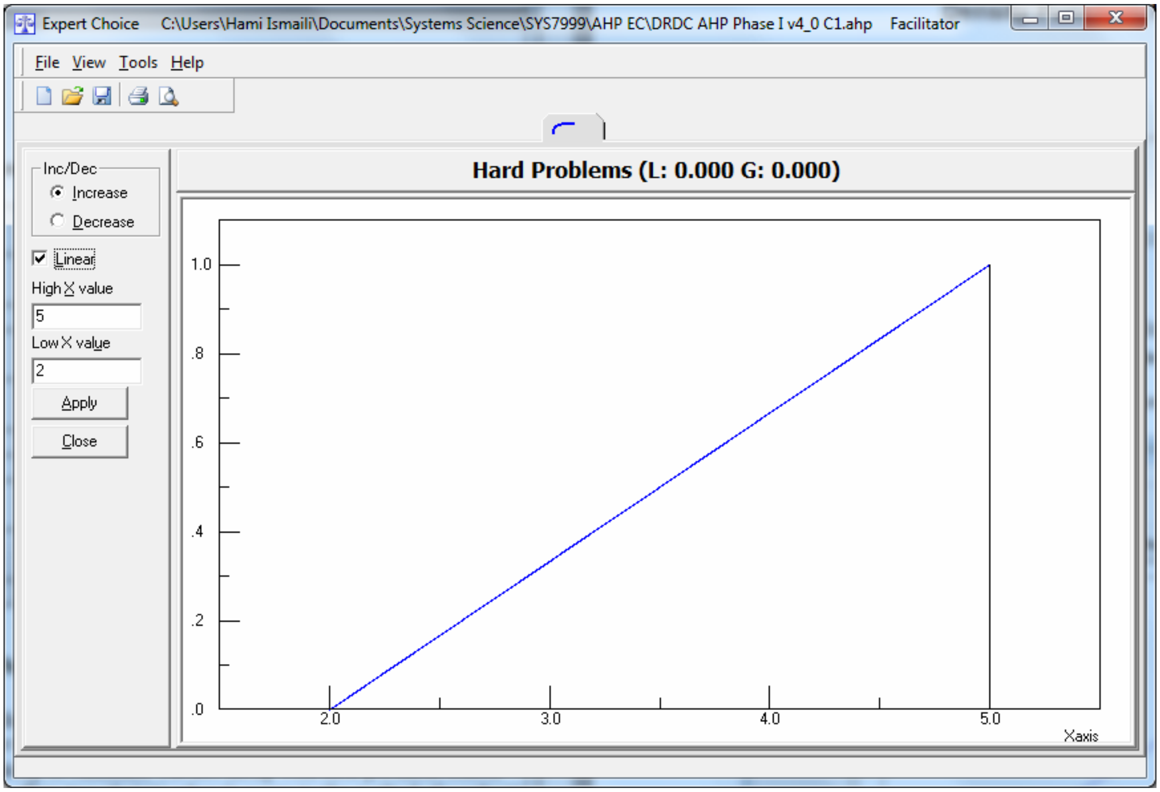


Figure 6. Utility function as defined in Expert Choice for “Hard Problems” (Source: Expert Choice, 2010)

The density function for “Originality” (Figure 7) behaves like the “Hard Problems” density of Figure 6 and is therefore assigned a utility function as in Figure 6 for “Originality”. The same can be said of the “Schedule Management” density (Figure 8) and the “Overall Quality” density (Figure 9). The resulting utility function assigned to these data score elements on scores 2 to 5 is found also in Figure 6.

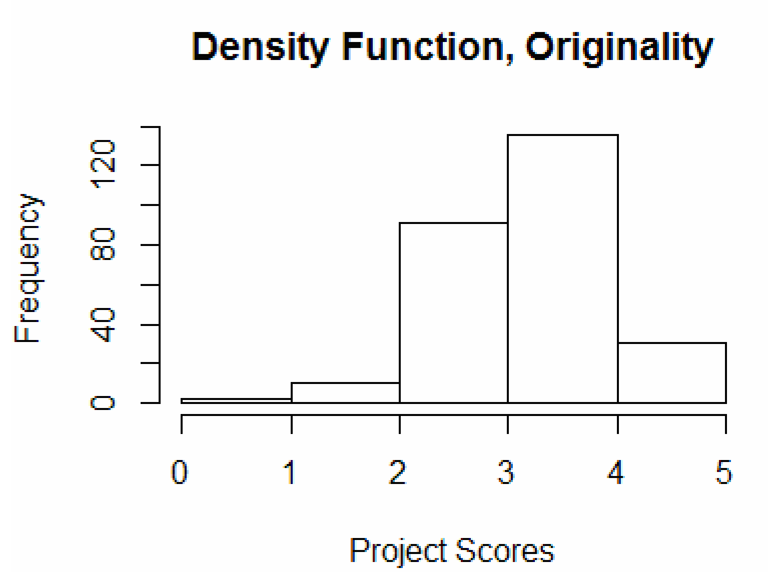


Figure 7. Histogram of scores for "Originality"

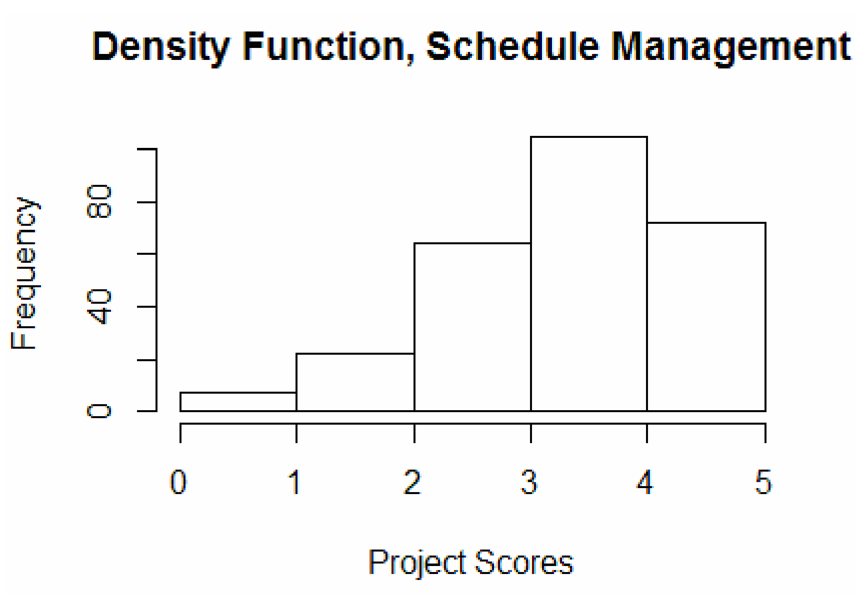


Figure 8. Histogram of scores for "Schedule Management"

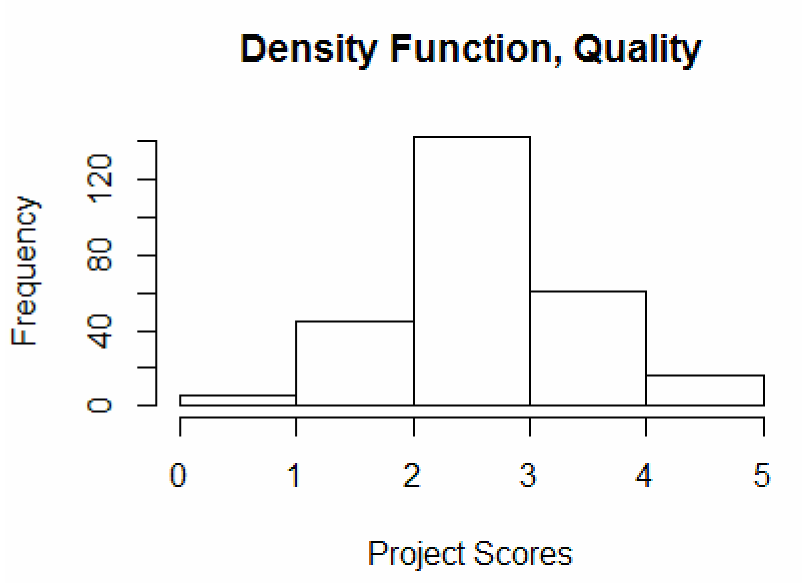


Figure 9. Histogram of scores for "Overall Quality"

Based on the density of the "Potential for Uptake" scores (Appendix B – Projects' Scores Distribution Analysis), its utility function is defined as follows in Figure 10 to cover the range of data from 1 to 5. Similarly, the density functions for "Leverage" (Figure 11) and "Scope" (Figure 12) are assigned the utility function as in Figure 10.

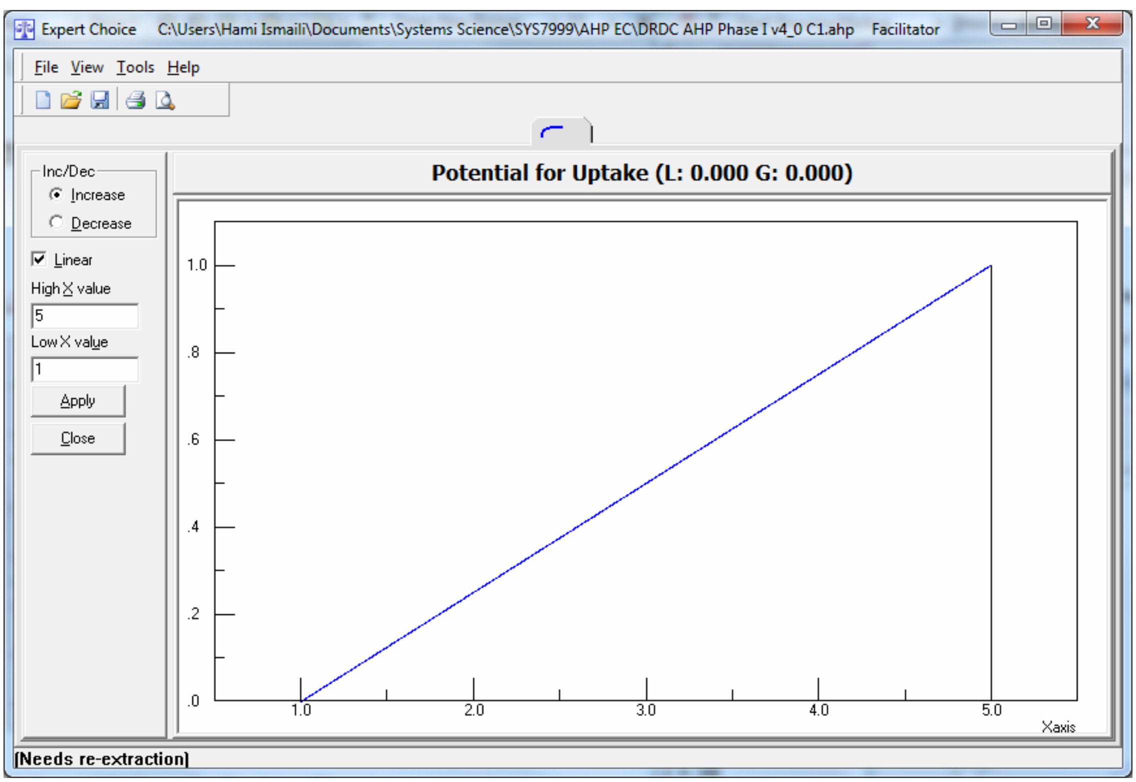


Figure 10. Utility function as defined in Expert Choice for "Potential for Uptake" (Source: Expert Choice, 2010)

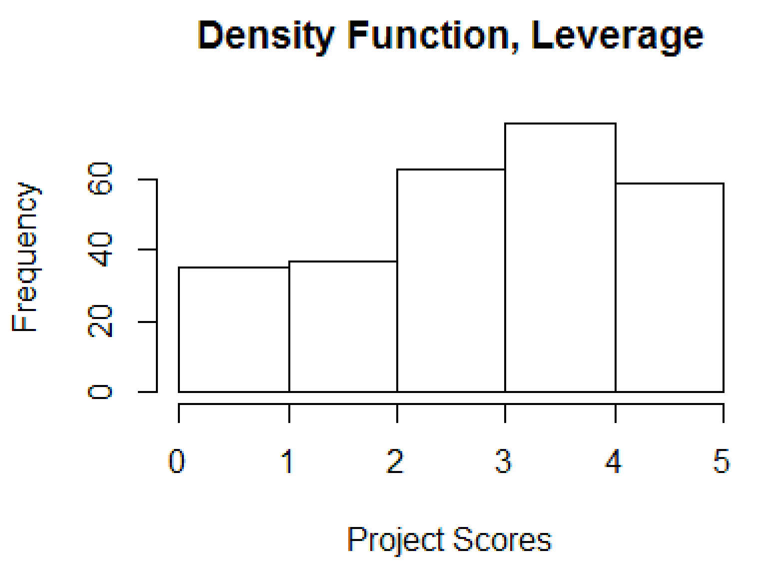


Figure 11. Histogram of scores for “Leverage”

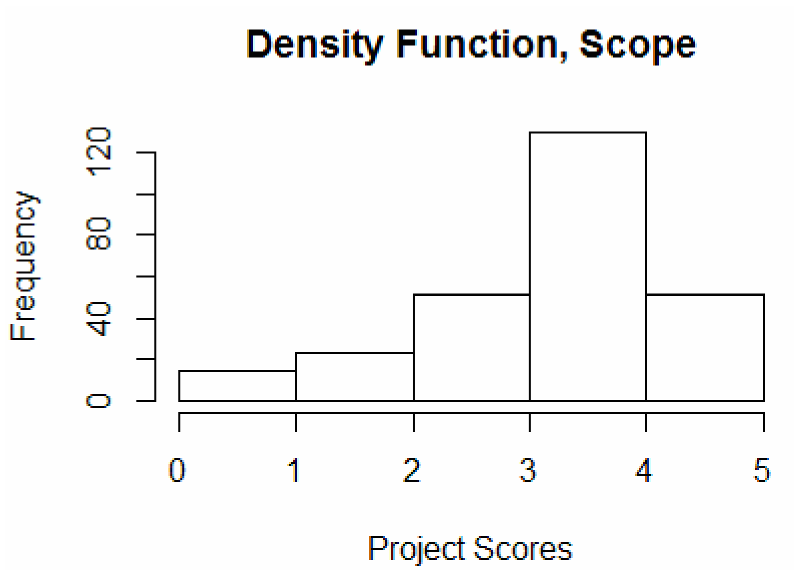


Figure 12. Histogram of scores for “Scope”

The utility function for “Budget Management” is a case where most recorded scores for the Thrusts are between 3 and 5 (Appendix B – Projects’ Scores Distribution Analysis). Therefore, in this case, the graph is created to project the values of that interval to the input of the algorithm. It means that any score value equal or less than 3 is treated as zero or the lowest level utility in AHP. Meanwhile, the values between 3 and 5 are projected linearly into utility values 0 to 1 interval on the vertical axis. The rule applied to select the range of data for projection in the utility function is based on density of more than 10 on a set of 269 project observations. The utility function for "Budget Management" is defined as follows in Figure 13 to cover the range of data from 3 to 5.

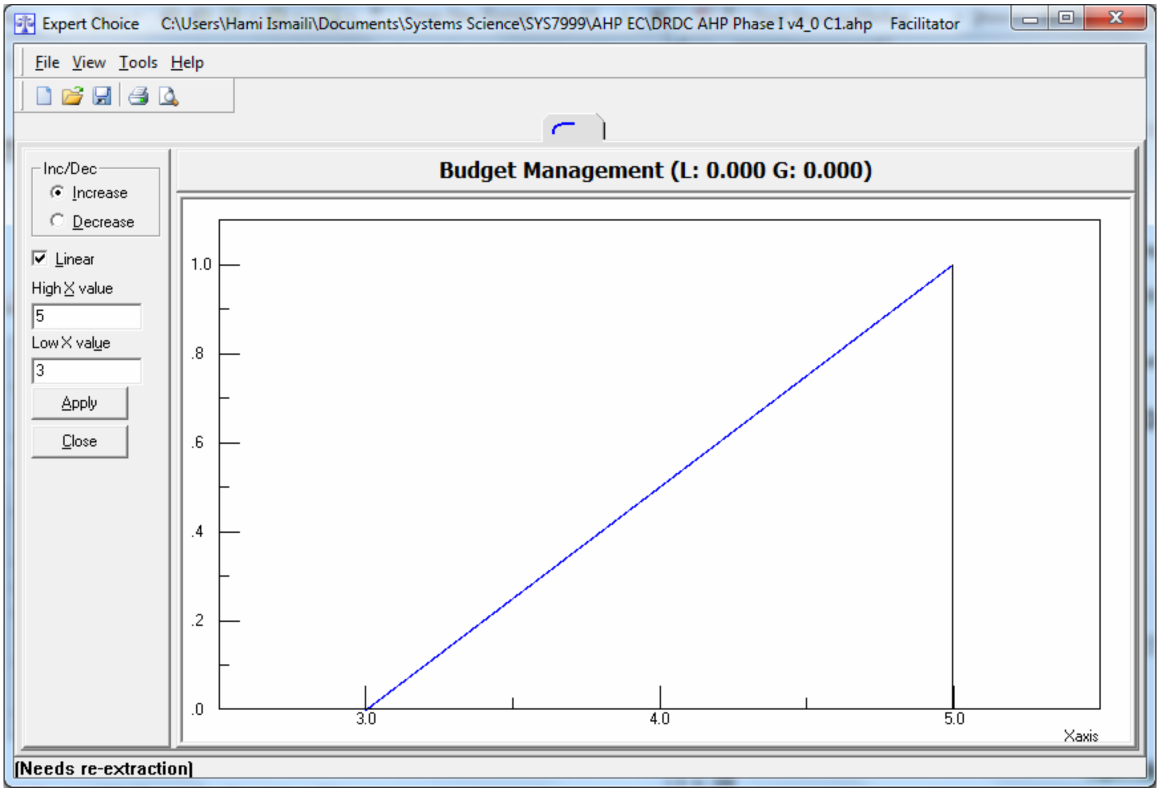


Figure 13. Utility function as defined in Expert Choice for "Budget Management" (Source: Expert Choice, 2010)

Table 15 summarizes the information with regard to the utility functions in the data grid used in the AHP model in *Expert Choice*.

Table 15. Utility functions assigned to criteria/subcriteria

Criteria/sub-criteria	**Formula**	**Minimum value**	**Maximum value**	**Type**
Hard Problems	Increasing	2	5	Linear
Originality	Increasing	2	5	Linear
Exploitation Plan	Increasing	0	1	Linear
Potential for Uptake	Increasing	1	5	Linear
Leverage	Increasing	1	5	Linear
Project Scope	Increasing	1	5	Linear
Schedule Management	Increasing	2	5	Linear
Budget Management	Increasing	3	5	Linear
Quality	Increasing	2	5	Linear

3.4.4 AHP Phase I – Ranking Thrusts

Once the data grid is filled (e.g., with the Thrusts scores as computed in Appendix A – CPME Data Analysis) and pairwise comparison of criteria is entered for the criteria of the hierarchy, *Expert Choice* synthesizes the data to produce the final ranked output by alternative. This consists of the ranking of candidate Thrusts along with their pertinent scaled weights. *Expert Choice* offers two choices when it comes to the method of synthesis.

'Ideal' mode gives the full weight of each objective to the best alternative. The other alternatives receive weights proportional to their relative weight to the best alternative. The weights are then normalized to sum up to one. The ideal mode is normally used when only the ranking of alternatives matters to the decision maker, and not their priorities. 'Distributive' mode allocates the weight of each objective to the alternatives in direct proportion of the alternative's weight under each objective. Distributive mode is normally used when measuring under condition of scarcity where assigning a resource to one alternative results in that resource being taken away from another. However distributive mode can result in rank reversal (Forman and Shelly, 2001).

In Phase I, the weights of all alternatives are of less interest and only the ranking is used to further process Thrusts. However in Phase II, there is a need to assign the resources proportional to the Thrusts' weight within each group. Therefore, the weight of each alternative matters in this problem. Therefore the 'Distributive' mode is selected in the subsequent analysis (Phase II).

In Phase I, the ranking is performed separately for each of the five clustered Thrust Groups of Table 13. Table 16 contains the results of ranking within each group in Phase I.

Table 16. Results of ranking of Thrusts within each group

Cluster	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**
Data Characteristics	**High DND fund**	**High DRDC fund**	**Low quantity of scientists**	**Low DND fund**	**Midrange DND and DRDC fund**
Thrust - Relative Rank					
1	17 (0.200)	30 (0.196)	23 (0.259)	24 (0.206)	22 (0.214)
2	6 (0.183)	19 (0.189)	15 (0.228)	21 (0.180)	2 (0.151)
3	13 (0.164)	26 (0.172)	16 (0.186)	1 (0.178)	12 (0.139)
4	7 (0.161)	3 (0.171)	18 (0.185)	8 (0.154)	29 (0.130)
5	20 (0.148)	28 (0.150)	5 (0.141)	9 (0.154)	14 (0.125)
6	4 (0.143)	25 (0.121)		10 (0.128)	11 (0.123)
7					27 (0.118)

3.4.5 AHP Phase II – Ranking clusters

In Phase I, the thirty Thrusts were clustered into five groups. This clustering was based on similarities between group members. The Thrusts were then ranked within each group. The design was to support the idea that diversity is conserved within DRDC's portfolio by rewarding the best Thrusts in each category with better funds.

In Phase II, the ranked Thrusts are regrouped. The firsts of each cluster in Phase I are put together into a new group, the 2nd ranked Thrusts of each cluster into the second group and so on as shown in Figure 14. The Thrusts which ranked the same in their group are coloured alike. Since Cluster 5 consists of 7 Thrusts, the sixth and seventh ranked Thrusts in Cluster 5 were both placed in one group. Since in Phase I each cluster contained a different quantity of Thrusts (5, 6, or 7), the selection process for the next phase of AHP is dependent of the population in each cluster. Table 17 contains the regrouping information from the original 5 clusters.

It is presumed that the groups containing the better ranked Thrusts will benefit from better funding. In Phase II, the resulting groups are again ranked themselves to obtain the weight of each group with respect to the main objective of the AHP problem.

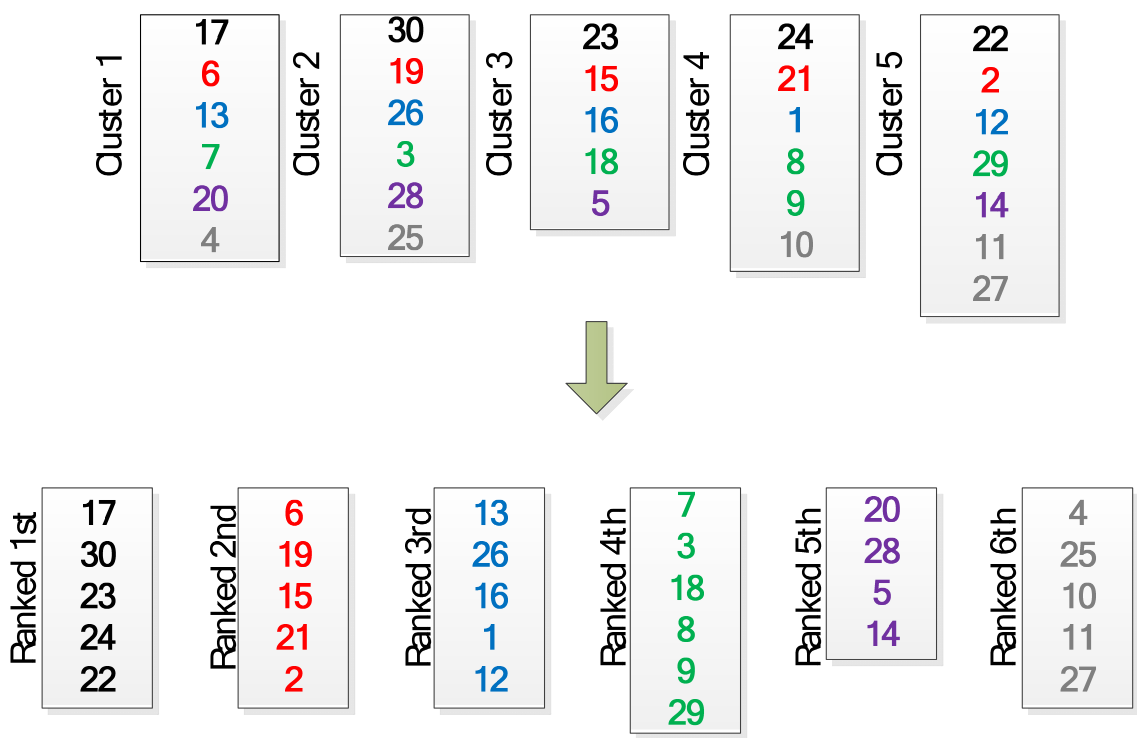


Figure 14. Selection rule for re-grouping of ranked Thrusts for Phase II

The six new clusters that are obtained are ranked using AHP. The group clusters are expected to preserve their order of ranking obtained in Phase I. However, it is of interest to obtain weights that determine their relative overall performance.

Table 17. New group allocation with ranked Thrusts

Phase II Thrust Groups	Thrusts
Group 1 - Ranked First	17, 30, 23, 24, 22
Group 2 - Ranked Second	6, 19, 15, 21, 2
Group 3 - Ranked Third	13, 26, 16, 1, 12
Group 4 - Ranked Fourth	7, 3, 18, 8, 9, 29
Group 5 - Ranked Fifth	20, 28, 5, 14
Group 6 - Ranked Sixth	4, 25, 10, 11, 27

The same AHP hierarchy structure as in Phase I is used to rank the new groups in Phase II. The alternatives are now the new groups formed in Phase II. However, in order to rank the groups, score representations for each group needs to be determined. Based on the discussion in Section 3.3 above, once again, the median for 'Scope' and 'Budget management' is used, and the arithmetic mean for the rest of the criteria are used to obtain overall scores for each group. The arithmetic mean and median are calculated through MS-Excel using the CPME data for project scores. Table 18 below contains the average scores used for each Thrust in Phase II of our method.

Table 18. Average scores for groups containing Thrusts

Group	Hard Problems	Project Originality	Exploitation Plan	Potential for uptake	Leverage	Project Scope	Schedule Mgt	Budget Mgt	Quality
1	3.73	3.67	3.97	3.92	3.77	3.67	3.91	4.83	3.58
2	3.70	3.49	3.30	3.46	3.37	3.80	3.70	4.74	3.13
3	4.04	3.77	2.06	3.29	3.41	3.88	3.92	4.75	3.15
4	3.52	3.53	2.19	3.24	2.92	3.98	3.62	4.74	3.01
5	3.69	3.74	1.40	2.73	2.74	3.25	3.59	4.75	2.89
6	3.64	3.70	0.79	2.93	2.90	3.78	4.11	4.87	2.93

Again the computations are facilitated by *Expert Choice* using the same hierarchy as before (Figure 3). However in Phase II, the alternatives are the ranked-group clusters of ordered Thrusts, instead of Thrusts themselves. The data-grid is made to reflect the overall scores of groups. The final product of this step is ranked groups which are classes of Thrusts. The results of Phase II of the AHP method is presented in Chapter 4, Results and Analysis.

This chapter demonstrated the methodology that is applied to the DRDC strategic program prioritization problem. It discussed the problem formulation using two different methods: Linear Programming (LP) and the Analytic Hierarchy Process (AHP). Although both utilized the scoring of projects from CPME as their input, their supplementary information was defined and extracted differently. Moreover, the LP model directly lays out the resource assignment between Thrusts where the AHP's output consists of the overall ranking of the Thrusts.

The next chapter presents the results of each method and provides an analysis of the results.

4 Results and Analysis

This chapter discusses the outcome of the LP model and AHP solution procedure as described in Chapter 3. It also presents an analysis of the methodologies applied to the DRDC problem. The problem at hand is to assign human resources of different skill sets to the suite of Thrusts to maximize the alignment of projects' progress with the Functional Planning Guidance (FPG) (DRDC, 2010b) and feedback from the Program Synopsis.

The outcome of the research will be presented as a model that ranks resource assignments to different research focus groups (Thrusts) to achieve maximum alignment with S&T governmental objectives. The ranked solutions represent the best results conforming to the strategic program prioritization problem. Once implemented, the model will generate a list of Thrusts with pertinent values for preference. Further, this model can be configured into appropriate processes to assigned human and financial resources to individual Thrusts.

Section 4.1 below, presents the result of the LP model in various contexts with respect to constraints. It aims to discover the behaviour of the applied LP algorithm in the DRDC's program formulation. Sensitivity analysis is then performed and displayed in Appendix F - LP Sensitivity Analysis for FTE Types, on the LP results considering important model elements to further analyze the solution. Section 4.2 presents the results of the AHP methodology and introduces steps to implement the ranking information to allocate resources to Thrusts. It then follows with sensitivity analysis with respect to the ranking of criteria and subcriteria. An overall comparison between the LP algorithm, AHP methodology and actual resource assignment of fiscal year 2010-2011 is presented near the end of this Chapter.

4.1 Results of LP Method

The solution to the LP model of Section 3.3 is obtained through *What's Best!* (Lindo Systems, 2011). This software is used due to its capability to handle larger data sets including the DRDC problem of size 360 decision variables and 797 constraints. Its easy interface with MS-Excel, and the familiarity of researcher with spreadsheet modelling, has also contributed to its selection.

The LP model is implemented through creating matrices in MS Excel. *What's Best!* provides tools to define the relationships between the constraints and objective function by linking the cells mathematically. The solution is presented in a separate sheet but in the same MS-Excel file that the formula and LP matrices are set up. *What's Best!* also provides various information with regard to the solution. It displays the number of variables and adjustable cells (decision variables) present in the formulation as well as possible warning and error messages. Appendix E–LP Solutions, displays the solution summaries obtained in one of the LP models presented in this section.

4.1.1 LP Solution

To demonstrate the effects of constraints on the result of LP solution, the results of the LP model are presented in two stages. The first LP model and solution deal with the problem with limited constraints, while the second set takes all the constraints into account. Refer to Appendix G – LP Results Analysis, for analysis of LP results.

The actual fund allocation for 2010-2011 is very similar to the output of LP with full constraints. In the LP results, the values for minimum thrust fund is lower than the actual value and the maximum fund allocation is higher than the maximum fund in the actual 2010-2011 allocations. The average is the identical for both, since calculation is based on division of total funds by the number of Thrusts.

However, result of LP for FTE allocation and the actual 2010-2011 FTE allocation display some differences. The values in the LP output are strictly set to the minimum or maximum allowable quantity for each Thrust (Thrust 4, Type 1 is set to 1.5, which is defined as a minimum requirement for this Thrust, where as Thrust 1, Type 11 is awarded 17, which is the maximum allowable value), except where the constraints do not allow it (i.e., Thrusts 2, Type 4 where the quantity of allocated FTE is 12 but the constraints are set at 10.5 and 21 for minimum and maximum). This occurs because LP awards resources to Thrusts that provide the highest benefit, but is bounded by constraints to meet the minimum requirements for each Thrust first.

Applying the values of actual 2010-2011 resource assignment to the benefit function in our LP model, yields the value of 37,263 benefit units for the objective function *Z* of the actual solution for 2010-2011. This value is slightly higher than the LP solution under full constraints.

The *Z* value for each LP solution is computed and displayed in Table 19 for full comparison. It is observed that the value is highest for the first solution with the FTE constraints removed. The lowest *Z* value belongs to the solution with all constraints taken into account. The actual resource assignment in 2010-2011 lies between the two theoretical values.

Table 19. The Z-value for different solution sets (in benefit units)

Solution	**Full constraints (Table)**	**Actual 2010-2011 resource assignment (Table)**	**Limited constraints (Table)**	**No constraints (Table)**
Z-Value (benefit units)	37,045	37,263	58,119	63,891

4.2 Results of AHP Method

The results of the AHP *Expert Choice* model formulation is presented by Thrusts rankings, and relative Thrusts comparisons. The Thrusts' weights with respect to the main objective are provided, hence showing its relative importance with respect to other Thrusts.

4.2.1 Phase II Results

The following Table 20 contains the results of the Phase II of the ranked Thrusts Groups. As noted previously, each group contains Thrusts that have different characteristics but are similar in performance and scoring from the Phase I rankings (as presented in Section 3.4.5). In Table 20, the weight of each ranked group that is provided in the second column under 'Priority' refers to the weight with respect to the main objective, DRDC Program efficiency.

Table 20. AHP model Phase II ranking of groups (Source: Expert Choice, 2010)

Group No.	**Thrusts Ranking (Phase I)**	**Thrusts Membership**	**Priority**	**Successive Weight gap**
1	1^{st}	17, 30, 23, 24, 22	0.215	-
2	2^{nd}	6, 19, 15, 21, 2	0.184	0.031
3	3^{rd}	13, 26, 16, 1, 12	0.167	0.017
4	$4^{th}+5^{th}$(9)	7, 3, 18, 8, 9, 29	0.160	0.007
5	5^{th}	20, 28, 5, 14	0.138	0.022
6	$6^{th}+7^{th}$ (27)	4, 25, 10, 11, 27	0.135	0.003

The above ranking could be used by DRDC to decide which groups get the higher proportion of the total funds. However, this priority ranking lacks direct guidance on the quantities of FTEs, as provided in the LP model results (Section 4.1.1 above). As observed in the table above, Groups 5 and 6 are very close in ranking, as well as Groups 3 and 4 (successive priority ranking weight gaps are less than 0.01). The gap between Groups 1, 2 and 3 are considerably larger, in addition to the distance between Groups 4 and 5. In the next section, the above ranking is applied to allocate resources to each Thrust.

4.2.2 AHP Comparative Results

This section applies the outcome of the AHP method to allocate human and financial resources to Thrusts. The result of the AHP consists of ranked Thrust groups with associated weights. These relative weights define the portion of resources that will be awarded to Thrusts Groups. Therefore the Thrusts within each group are treated with the same importance and need to share the amount of the resources allocated to them. Figure 15 displays the relative weight of Thrust Groups and proportional share of resources.

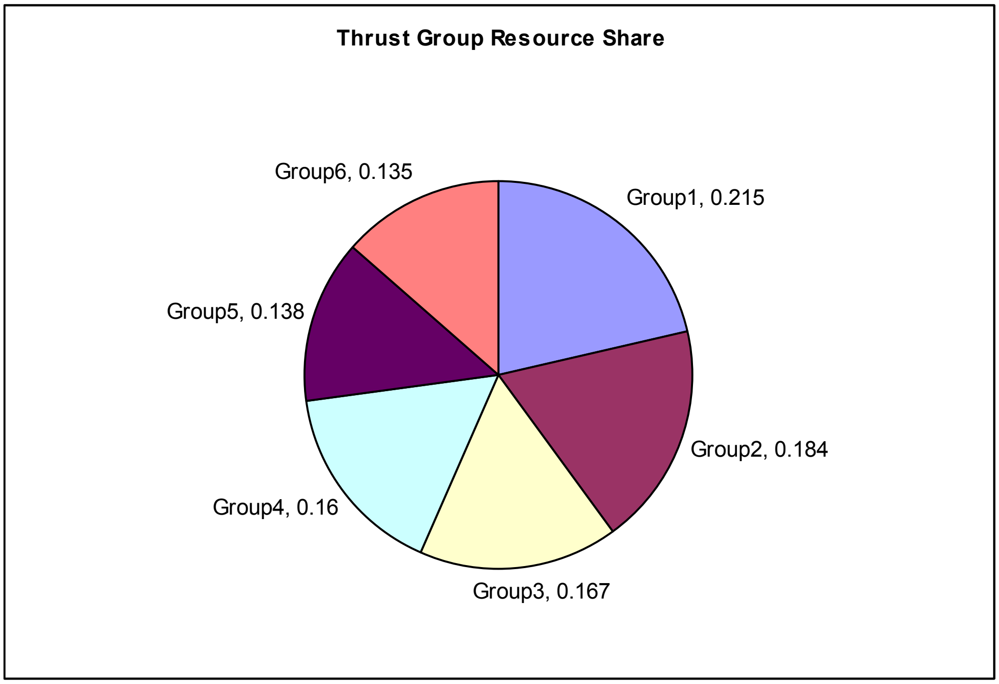


Figure 15. Share of Thrust groups based on AHP ranking

It is possible to multiply directly the weight of each Thrust Group by the quantity of FTEs and DRDC funds and distribute a share to each. However, in reality, each Thrust requires a unique amount of FTEs and funds. For example, a Thrust in Group 1 might be a small Thrust with low requirements of resources. It is placed in that group solely for the reason of being best in its category of Thrust in Phase I. Therefore it is possible to find that Group 1 does not need all the resources allocated to it. Then the resources can be taken to the next group of Thrusts.

The allocation of resources in this manner is very similar to how the LP algorithm handles the resources. In this case the allocation share to each Thrust Group is another set of constraints. The LP model in section 3.3 can be reused with the benefit function filled out with numbers from 6 to 1 for Thrusts depending on which Group in Phase II they belong to (6 being the highest benefit and 1 the lowest). However the FTE allocation in the LP model of section 3.3 has characteristics that the AHP's output with uniform benefit value across Thrust types cannot accommodate. The procedures for applying the AHP ranking to allocate resources are discussed next. The fund allocation is discussed first as it involves less complexity.

DRDC fund allocation

Figure 16 is the flowchart for distributing the DRDC fund among Thrusts. The logic is to divide the share of each Thrust Group, then start from the top group to distribute among its Thrusts. If the share of Group 1 is more than what all the Thrusts are asking for, then it is necessary to provide them with their requests and carry forward the remainder of funds to Group 2. However, if the total request by Thrusts is more than the allocated budget, then the assumption is to provide Thrusts with equal percentages of what their asking for. e.g., all Thrusts get 68% of their requested budget. These steps are continued until all Thrust groups are processed all funds are allocated.

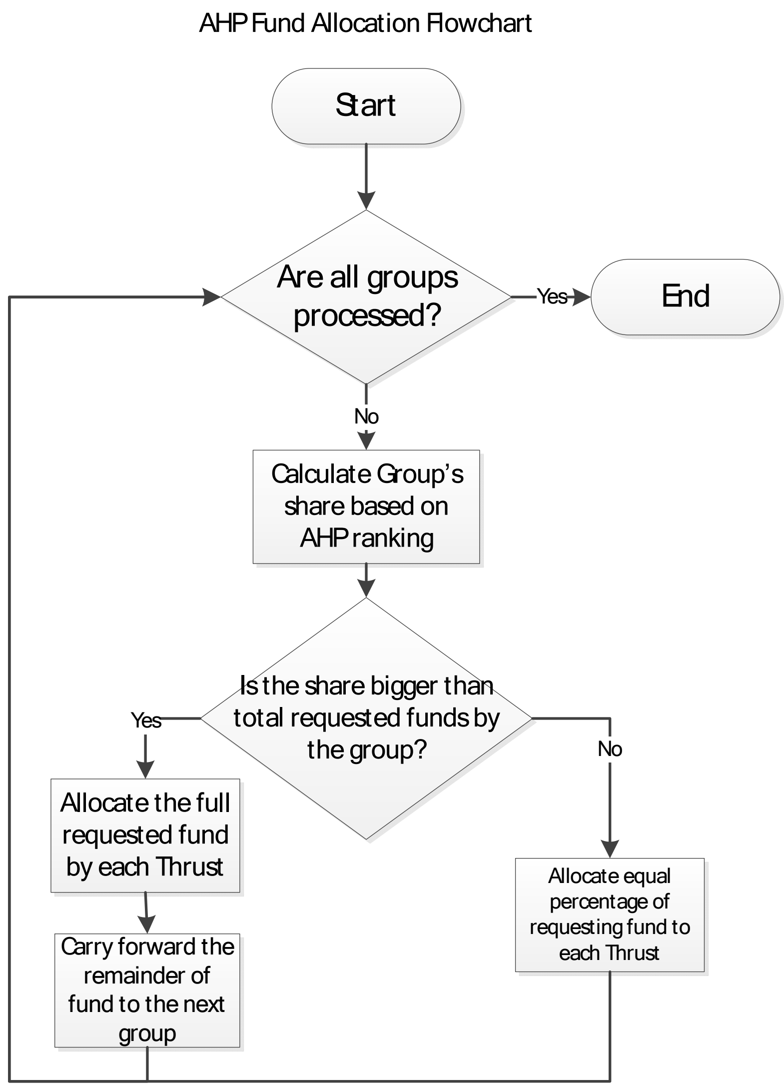


Figure 16. Fund allocation flowchart with AHP rankings

The algorithm in Figure 16 reserves the share of each Thrust Group and awards any leftovers to the next group down in the rank. The calculations for the DRDC fund allocation based on AHP ranking is implemented in MS-Excel sheets. Appendix M- "Resource Allocation by AHP Rankings" provides the tables that demonstrate the allocation calculations. Table 21 contains the result of the fund distributions among Thrusts. The budget allocation is displayed in the following Table 21.

Table 21. DRDC fund allocation by AHP method

Thrusts	Requested fund (M$)	Percentage rewarded	Fund awarded (M$)
1	1.00	61.71%	0.62
2	1.50	98.77%	1.48
3	1.70	68.86%	1.17
4	2.00	63.75%	1.28
5	1.50	65.16%	0.98
6	2.00	98.77%	1.98
7	1.50	68.86%	1.03
8	1.60	68.86%	1.10
9	0.50	68.86%	0.34
10	1.30	63.75%	0.83
11	0.50	63.75%	0.32
12	1.20	61.71%	0.74
13	3.00	61.71%	1.85
14	1.30	65.16%	0.85
15	0.75	98.77%	0.74
16	1.50	61.71%	0.93
17	1.30	100%	1.30
18	1.30	68.86%	0.90
19	2.00	98.77%	1.98
20	1.80	65.16%	1.17
21	0.60	98.77%	0.59
22	1.30	100%	1.30
23	0.60	100%	0.60
24	1.40	100%	1.40
25	1.30	63.75%	0.83
26	2.50	61.71%	1.54
27	2.10	63.75%	1.34
28	2.60	65.16%	1.69
29	1.30	68.86%	0.90
30	2.20	100%	2.20

The AHP results show a lower standard deviation for the DRDC fund calculations. The minimum value ($0.32M) is higher than the 2010-2011 minimum amount ($0.27M), where the maximum value ($2.2M) is lower than the actual 2010-2011 allocation ($2.5M). This is the opposite outcome of LP with respect to the 2010-2011 allocation, where the minimum is lower and maximum is higher.

FTE allocation

Allocating FTE with the ranking information is similar to the procedure for the DRDC funds. However, the 11 FTE types add to the complexity of distribution. It is possible that Thrusts in the lower ranked groups will encounter a situation where the FTE type they may require is no longer available. This is a management decision to consider whether other FTE types can replace what the Thrusts are asking for. For the purpose of allocation in this thesis, it is assumed that when an FTE type is no longer available, another type will be assigned. Since the process starts from the higher rank Thrust Groups, the best Thrusts will be awarded most or all of their requirements. Moreover, the portion of FTEs dedicated to each Thrust Group ensures that all Thrusts are awarded resources. Figure 17 is the flowchart for the procedure of allocating FTE resources to Thrusts based on AHP rankings.

The calculations for the FTE resources allocation based on AHP ranking is carried out in MS-Excel sheets. Appendix M - Resource Allocation by AHP Rankings provides the spreadsheet tables for the FTE allocations to Thrusts.

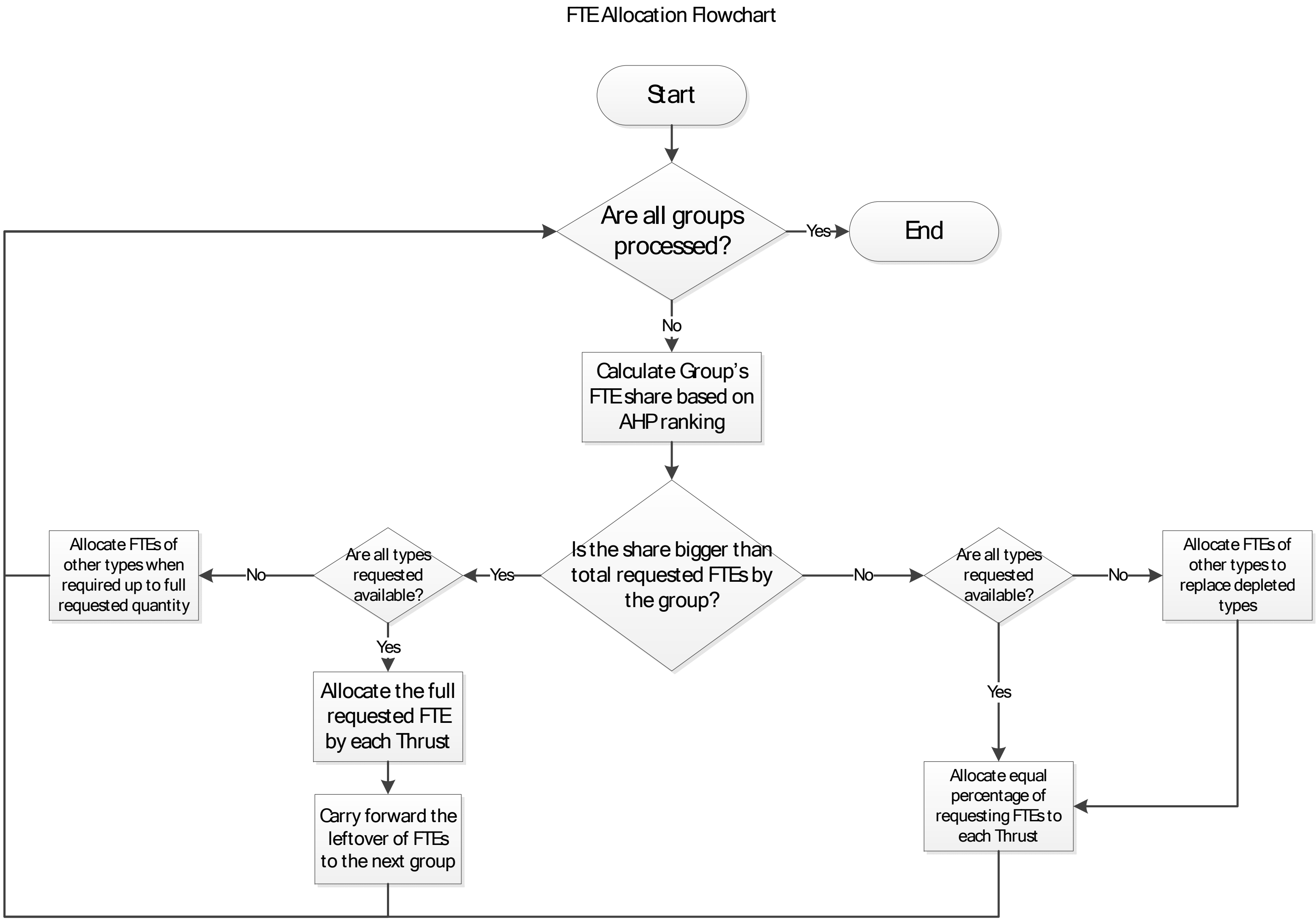


Figure 17. FTE allocation flowchart with AHP rankings

The FTE resource allocations with AHP rankings are displayed in Table 22. The values are obtained through MS-Excel sheet that were set up with the Thrust group values. The far right column, “Percentage of requested FTEs awarded”, is the ratio of actual allocated FTEs over the requested quantity by the Thrust. The percentage value is equal for all the Thrusts that were in the same Thrust group.

Table 22. FTE allocation by AHP method

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*	*Percentage of requested FTEs awarded*
1	0	0	0	3.12	0	0	0	0	0	0	8.84	52%
2	2.4	0	0	16.8	0	0	2.4	0	0	0	2.4	80%
3	0	0	3.71	0	0	0	0	13.78	2.12	1.59	0	53%
4	1.41	1.41	4.23	1.88	1.41	1.41	3.29	1.41	6.11	1.41	0	47%
5	7.3	0	2.19	4.38	0	0	0	0	0	0	0	73%
6	3.2	2.4	19.2	4	6.4	3.2	0	0	9.6	12.8	2.4	80%
7	1.59	0	1.59	4.24	0	15.9	1.59	0	5.83	0	0	53%
8	5.83	0	3.71	1.59	0	0	0	0	0	0	0	53%
9	0	0	1.59	5.3	0	0	2.12	0	0	0	0	53%
10	2.35	3.76	0	1.88	0	1.41	0	1.41	0	1.88	1.88	47%
11	2.82	6.58	4.23	1.41	1.88	1.41	1.41	0	1.41	0	0	47%
12	0	0	1.56	1.56	1.56	1.56	4.16	4.68	2.08	1.56	0	52%
13	2.08	4.16	2.08	1.56	0	1.56	6.24	8.84	11.44	2.6	1.56	52%
14	2.19	0	2.19	2.19	3.65	5.11	8.03	2.19	6.57	0	0	73%
15	0	0	0	9.6	0	0	0	0	0	0	0	80%
16	0	0	7.8	1.56	0	0	1.56	1.56	0	0	0	52%
17	2.34	0	3.9	2.34	2.34	0	8.58	2.34	13.26	0	0	78%
18	0	0	0	4.77	1.59	0	0	0	1.59	1.59	0	53%
19	0	0	0	0	0	2.4	0	0	0	4.8	0	80%
20	5.11	2.19	2.19	2.19	2.19	0	2.19	0	0	2.92	0	73%
21	0	0	0	7.2	0	0	0	0	0	4	2.4	80%
22	0	0	0	2.34	0	0	0	0	0	2.34	21.06	78%
23	0	0	0	0	0	0	0	0	0	0	10.92	78%
24	0	0	0	0	0	0	0	0	0	3.12	14.04	78%
25	1.41	0	0	1.41	0	0	0	1.41	0	7.99	1.88	47%
26	0	0	0	0	1.56	0	0	15.6	0	2.08	1.56	52%
27	4.23	0	1.41	2.35	0	0	0	0	0	1.41	2.82	47%
28	3.65	17.52	0	2.19	0	0	0	0	0	0	0	73%
29	0	2.65	9.01	0	1.59	0	1.59	0	2.12	1.59	2.12	53%
30	5.46	9.36	16.38	4.68	2.34	2.34	3.12	2.34	2.34	0	0	78%

Thrust Group 6, the lowest ranked Thrust group, is faced with lack of required resources. As displayed in Table 23, there are surplus of Types 8, 9, 10 and 11. However Types 1 to 7 are scarce. Therefore FTEs from the first types are applied instead of the latter assuming some level of practical substitutability among FTE types.

Table 23. AHP FTE allocation, Thrust Group 6

Thrust	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
4	1.41	1.41	4.23	1.88	1.41	1.41	3.29	1.41	6.11	1.41	0
25	1.41	0	0	1.41	0	0	0	1.41	0	7.99	1.88
10	2.35	3.76	0	1.88	0	1.41	0	1.41	0	1.88	1.88
11	2.82	6.58	4.23	1.41	1.88	1.41	1.41	0	1.41	0	0
27	4.23	0	1.41	2.35	0	0	0	0	0	1.41	2.82
Requested FTEs	33.84			21.15				11.75		19.27	
Available FTEs	31.47			0.52				33.72		22.71	
Balance	-2.37			-20.63				21.97		3.44	

Thrust Group 6, being the last ranked group, is penalized with assignment of alternate FTE types. Upon decision makers' judgment, this penalty can be distributed equally among all or some Thrusts.

The resource allocation in Table 23, in reality looks like Table 24. The FTEs of type 8, 9, 10 and 11 are used as substitutes for FTE types 1 to 7.

Table 24. Actual Thrust Group 6, AHP FTE allocation

Thrust	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
4	1.19	1.19	4.01	0	0	0	0.52	5.81	10.51	1.9	0
25	1.19	0	0	0	0	0	0	5.81	0	8.48	2.37
10	2.13	3.54	0	0	0	0	0	5.81	0	2.37	2.37
11	2.6	6.36	4.01	0	0	0	0	0	5.81	0	0
27	4.01	0	1.19	0	0	0	0	0	0	1.9	3.31

The result of AHP for FTE allocation demonstrates similarities to the 2010-2011 allocations. Unlike LP with extreme values for its results, both AHP and 2010-2011 data are spread (between 47% to 100% of the requested funds). The minimum FTE assignment by AHP is 7.2 to Thrust 19, where the actual 2010-2011 assignment is $4.23M for the same Thrust. The maximum FTE allocation displays some difference as well with $63.2M for AHP and $55.72 for 2010-2011 data. However, the standard deviation for the result of AHP model is 12.71, which is close to the actual data (2010-2011) at 12.88.

The AHP method has awarded Thrust Group 6 with only %47 of the total requested fund by its Thrusts. In the current process at DRDC, it is estimated that Thrust will be awarded at least %50 of their requested resources.

AHP Results Analysis

Comparing the resource allocation tables for both AHP and LP for FTE and DRDC funds, the major difference falls in the way LP handles the assignment. The values are either lower bound or upper bound of the constraints. LP first satisfies the minimum requirements of all Thrusts, and then allocates the remainder of resources to Thrusts with higher benefit. That is the case for both FTE allocation and DRDC funds.

This risk is dampened in AHP by allocating the resources to Thrust Groups. The Thrusts within each Thrust Group benefit from the allocated resources proportional to their requirements. Therefore, the resource scarcity is distributed among Thrusts equally within a Thrust Group that are similar in performance. The allocation to Thrust Groups is decided by AHP based on the collective performance of Thrusts within each group.

Table 25 demonstrates an overall view of the DRDC fund allocation between the AHP, LP and the actual 2010-2011 fund allocation. The standard deviation in LP is higher than the other two, as is evident by LP's minimum and maximum funds allocation. However, the AHP model has narrowed the gap between the best and worst Thrusts.

Table 25. Comparison of fund allocation between LP and AHP methods and actual 2010-2011 allocations at Thrust level

Results	**Minimum ($M)**	**Maximum ($M)**	**Standard Deviation**
LP Results (Table)	0.25	2.50	0.551
Actual allocation (Table)	0.27	2.48	0.515
AHP Results (Table 21)	0.32	2.20	0.483

The result of AHP for FTE allocation demonstrates a smoother distribution of resources among Thrusts than the LP. The AHP model only uses the requested fund by Thrusts as its input, unlike the LP where minimum is also taken into account. However the minimum FTE assignment by AHP is 7.2 in Thrust 19, higher than the LP's minimum assignment of 4.5 for the same Thrust (Table 26). The standard deviation for the result of AHP model (12.71) is closer to the 2010-2011 data compare to the LP model (12.39).

Like the fund allocation results, the FTE allocation in LP also starts by meeting the minimum requested FTEs in each Thrust followed by Thrusts with higher benefits, up to their maximum total allowable by the constraints. Operationally, awarding all the resources a Thrust asks for, or half of what it asks for (deemed minimal operational needs for that Thrust), introduces some risks in the management of the projects' progress. AHP's logic in allocation allows 100% allocation to a Thrust only when the total resources asked by a Thrust Group is equal (or less) than the allocated budget determined through the AHP method. Otherwise, all Thrusts within a Thrust Group will receive an equal percentage of what they have individually asked for.

Table 26. Comparison of FTE allocation between LP and AHP methods and actual 2010-2011 allocations at Thrust level

Results	**Minimum (FTEs)**	**Maximum (FTEs)**	**Standard Deviation**
LP Results (Table)	4.5	51.5	12.39
Actual allocation (Table)	4.23	55.72	12.88
AHP Results (Table 22)	7.2	63.2	12.71

Comparing the FTE allocation of AHP among individual Thrusts (Table 27) shows that 11 Thrusts have received higher number of FTEs (more than %10) compare to the actual 2010-2011 allocation (Thrusts 2, 5, 6, 12, 14, 17, 18, 19, 20, 21 and 30). Only 6 of these Thrusts (2, 6, 17, 19, 21 and 30) belong to the higher ranked Thrust Groups (Thrust Groups 1 and 2). In the Phase II of the AHP method, the share of each Thrust Group is determined based on the combined performance of Thrusts within each Thrust Group. However in LP, each Thrust is processed individually and is awarded resources based on its own merit alone. This contributes to the variation of FTEs between the AHP and LP methods.

Table 27. Comparison of AHP results with actual 2010-2011 FTE allocation

Thrust	Actual	AHP	% Change	Thrust	Actual	AHP	% Change
1	17.93	11.96	-33	**16**	13.25	12.48	-6
2	20.13	24	19	**17**	27.47	35.1	28
3	29.32	21.2	-28	**18**	7.9	9.54	21
4	24.25	23.97	-1	**19**	4.23	7.2	70
5	11.1	13.87	25	**20**	7.25	18.98	162
6	55.72	63.2	13	**21**	10.05	13.6	35
7	42.3	30.74	-27	**22**	25.02	25.74	3
8	14.75	11.13	-25	**23**	11.7	10.92	-7
9	9.62	9.01	-6	**24**	16.65	17.16	3
10	13.83	14.57	5	**25**	19.01	14.1	-26
11	23.85	21.15	-11	**26**	28.81	20.8	-28
12	16.48	18.72	14	**27**	13.2	12.22	-7
13	55.09	42.12	-24	**28**	24.09	23.36	-3
14	23.5	32.12	37	**29**	21.1	20.67	-2
15	9.8	9.6	-2	**30**	38.46	48.36	26

4.2.3 AHP Sensitivity Analysis

AHP sensitivity analysis is accommodated by *Expert Choice*. Various graphical tools are provided in the software for this purpose. The sensitivity of the alternatives to the changes in the priorities of criteria and subcriteria can be verified dynamically. *Expert Choice* allows the decision maker to perform the analysis from any node in the hierarchy of Figure 3. The following examine the sensitivity analysis of the AHP Phase II model results.

Analysis of the criteria

There are 4 main criteria in the hierarchy of Figure 3. The objective is to determine whether an alternative could be sensitive to small changes to the weight of a particular criterion. Different values of weights for each criterion are examined to see the effect on the resulting priority ranking of the group alternatives. Through *Expert Choice*'s interactive sensitivity analysis, the amount of increase/decrease required to disturb the ranking are determined. The weights of alternatives are displayed on the right side of each graph in Figure 18 through Figure 26 below. The weights of alternatives change dynamically as the weights of criteria are modified. The solution model is based on the ranking of Thrusts in Phase I. Therefore, only the ranges of criteria weight that would affect the ranking of Thrusts are analyzed. There are four bars that can be adjusted in the dynamic sensitivity analysis window, modifying the weights of criteria.

For the purpose of sensitivity analysis, Cluster Group 1 with its five Thrusts has been selected. Figure 18 displays the weighting scheme of Thrusts and criteria as outputted through synthesis of judgements by decision makers.

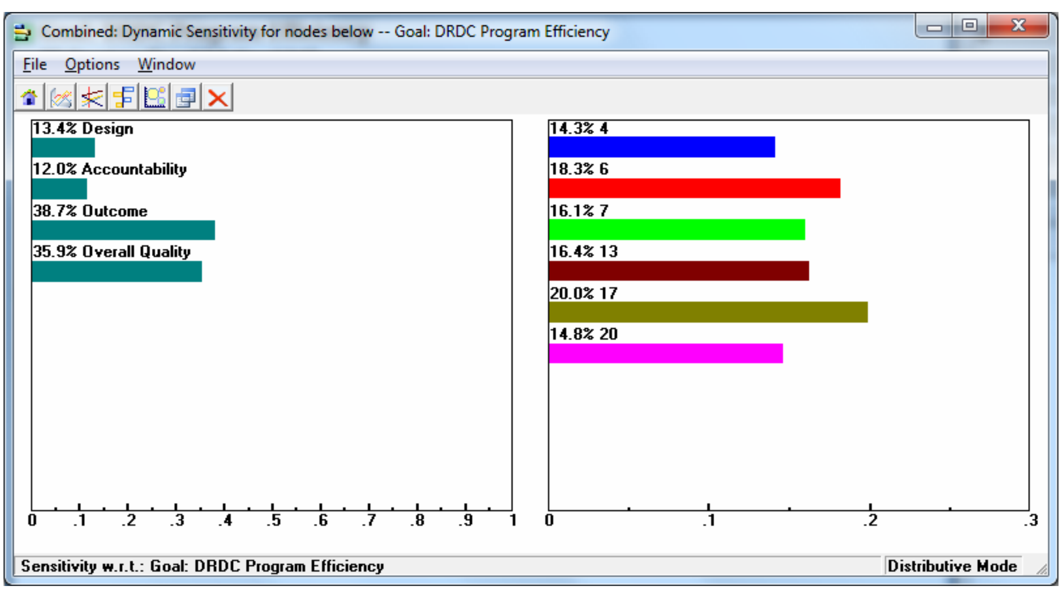


Figure 18. Weights of criteria and alternatives for Cluster Group 1 (Source: Expert Choice, 2010)

(1) **Design Criterion Sensitivity**: As shown in Figure 19, increasing the weight of 'Design' until it reaches 0.358 disturbs the original ranking, an increase of 0.224 (+167%) in weight from its original weight value of 0.134. This implies that the current Groups ranking is relatively insensitive to an improvement (increase) in 'Design' weighting over other criteria.

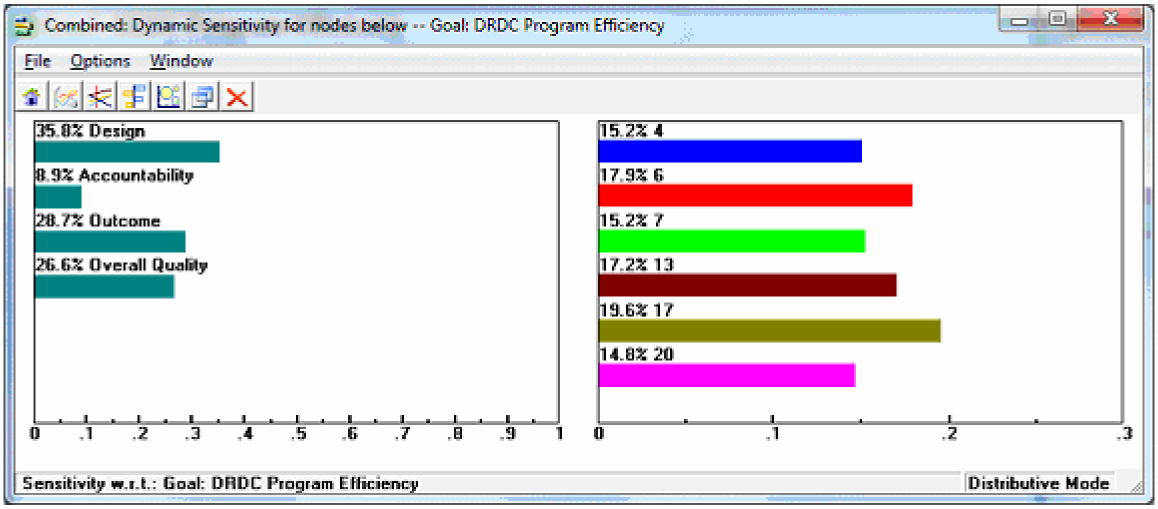


Figure 19. Sensitivity analysis, 'Design' weight increase for Cluster Group 1 (Source: Expert Choice, 2010)

Decreasing the 'Design' weight downward below a value of 0.103 (from 0.134 or -23%) introduces a change in Thrusts ranking. Therefore the model is much more sensitive to decrease in the 'Design' weight than it is to an increase.

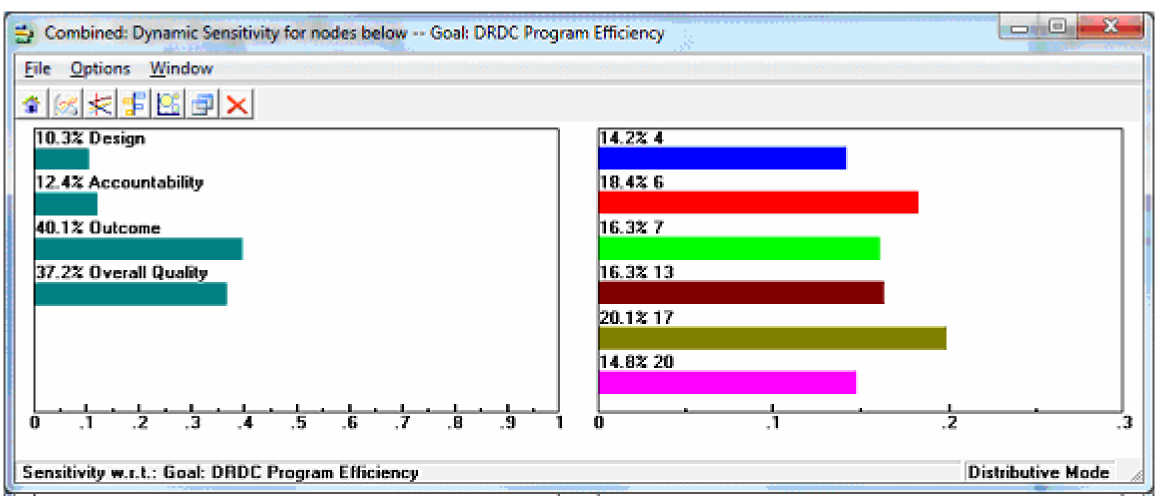


Figure 20. Sensitivity analysis, 'Design' weight decrease for Cluster Group 1 (Source: Expert Choice, 2010)

(2) **Accountability Criterion Sensitivity**: Pushing the weight of 'Accountability' to 0.541 will result in changes in ranking (Figure 21), an increase of 0.421 from the original weight of 0.12 (or +350%, Figure 18). Given the large relative change in increasing weight before a ranking change occurs, then the current ranking (Figure 18) is not sensitive to 'Accountability' weight increases.

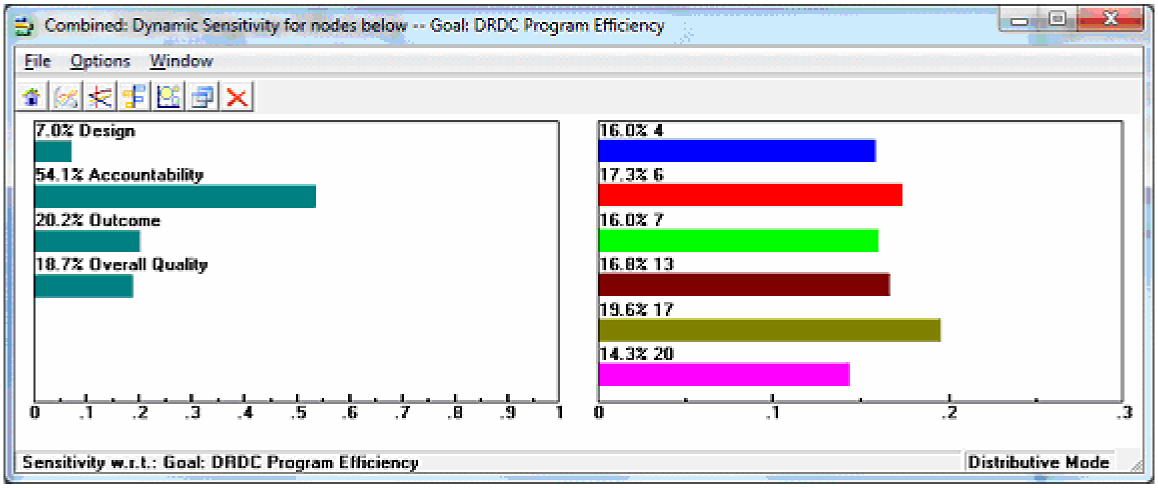


Figure 21. Sensitivity analysis, 'Accountability' weight increase for Cluster Group 1 (Source: Expert Choice, 2010)

Decreasing the weight of 'Accountability' down to 0 does not introduce any changes in the ranking of Thrusts from the original ranking of Figure 18, as is shown in Figure 22 below. Therefore the current ranking (Figure 18) is not sensitive to 'Accountability' weight decreases. Overall the ranking results are not sensitive to increases or decreases to the 'Accountability' criterion.

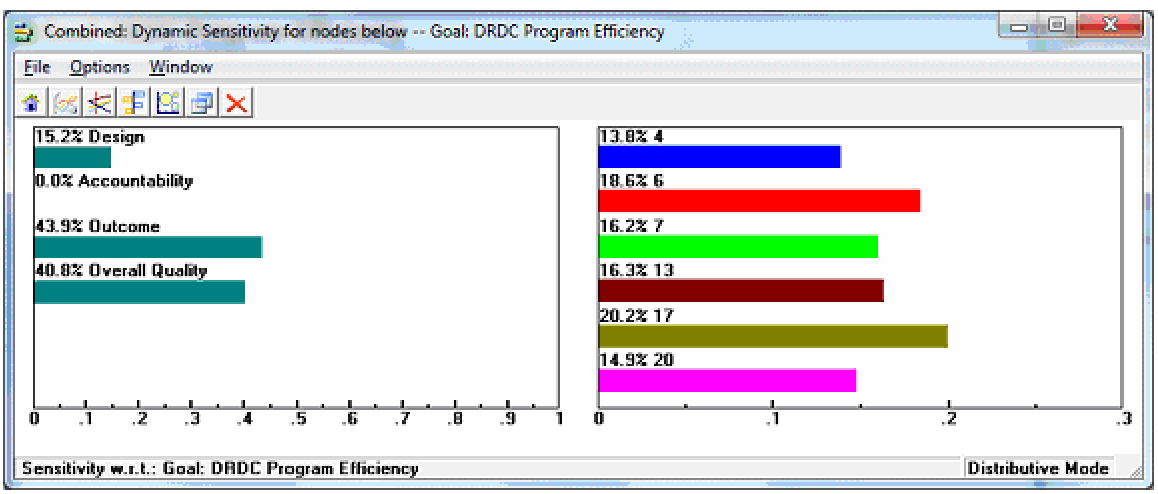


Figure 22. Sensitivity analysis, 'Accountability' weight decrease for Cluster Group 1 (Source: Expert Choice, 2010)

(3) **Outcome Criterion Sensitivity**: Increasing the weight of 'Outcome' creates changes in ranking when it reaches 0.413 (Figure 23) an increase of 0.026 from its original value of 0.387 (+7%) as noted in Figure 18. This relatively small shift in weight indicates that the Figure 18 ranking is sensitive to the 'Outcome' criterion weighting.

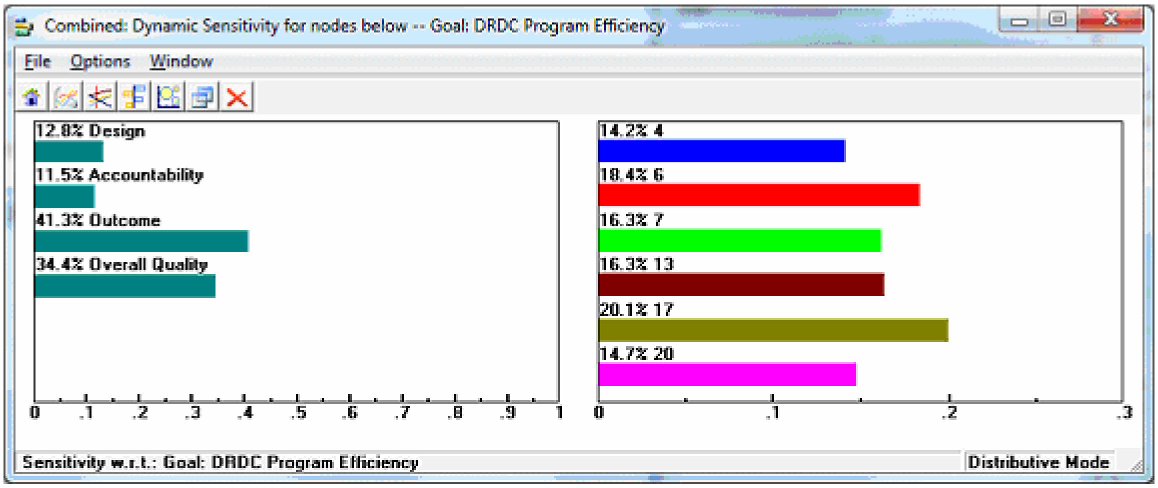


Figure 23. Sensitivity analysis, 'Outcome' weight increase for Cluster Group 1 (Source: Expert Choice, 2010)

Decreasing the weight of 'Outcome' down to 0.217 (from 0.387) introduces change in ranking, which is a decrease of 0.170 (or -44%). Thus, the current ranking is less sensitive to decreasing weights of the 'Outcome' criterion (Figure 24).

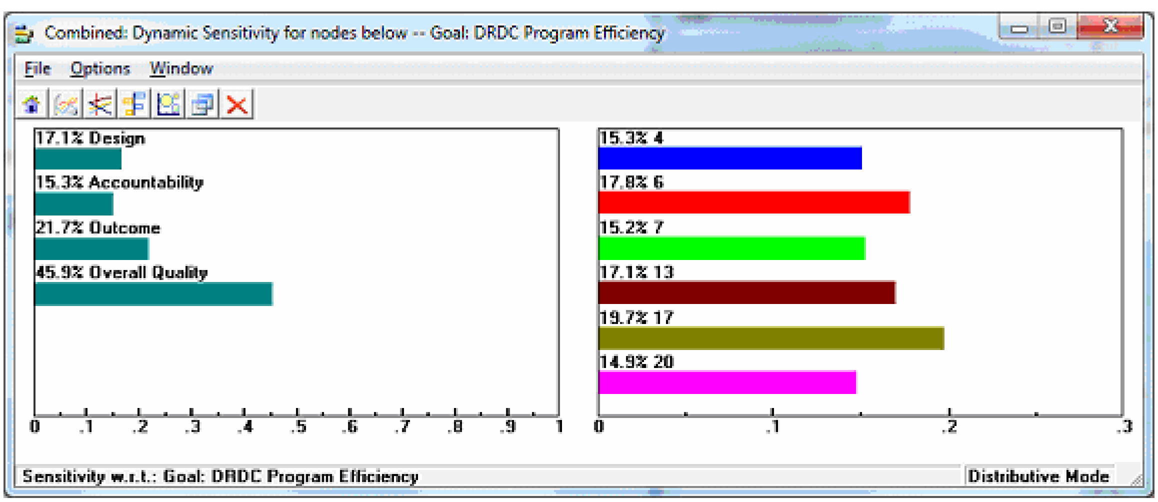


Figure 24. Sensitivity analysis, 'Outcome' weight decrease for Cluster Group 1 (Source: Expert Choice, 2010)

(4) **Overall Quality Criterion** Sensitivity: Pushing the weight of 'Overall Quality' higher from its original value of 0.359 (Figure 18) creates changes in ranking when it doubles and reaches 0.707, an increase of 0.348 (+97%, Figure 25). Thus, the original ranking is not sensitive to increasing changes to the 'Overall Quality' criterion.

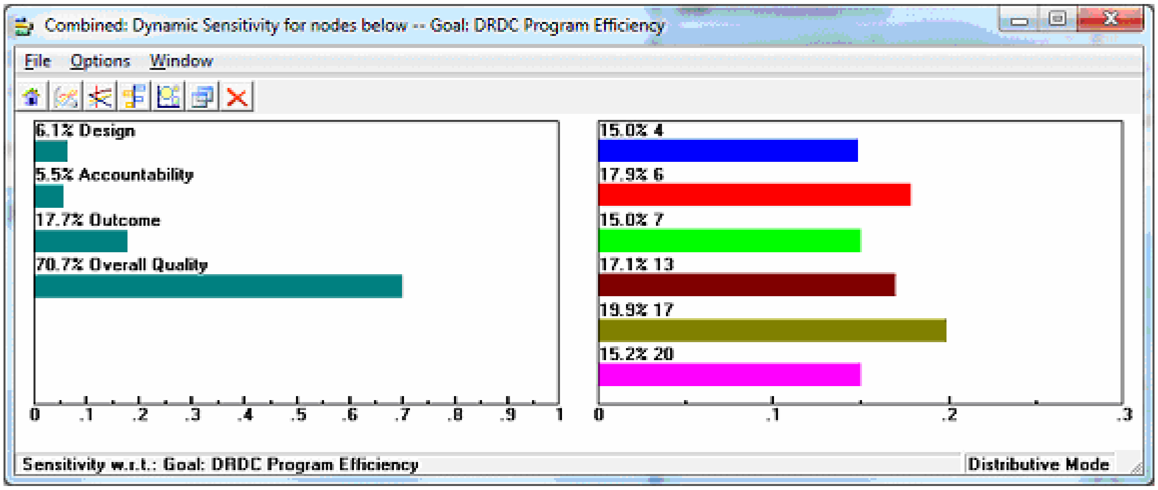


Figure 25. Sensitivity analysis, 'Overall quality' weight increase for Cluster Group 1 (Source: Expert Choice, 2010)

Similarly, decreasing the weight of 'Overall Quality' down to 0.299 (from 0.359) introduces change to the original ranking. However, this change is a small relative shift in weight (-17%) and therefore indicates that the original ranking of Figure 18 is more sensitive to downward shifts in the 'Overall Quality' rather than an increase (Figure 26).

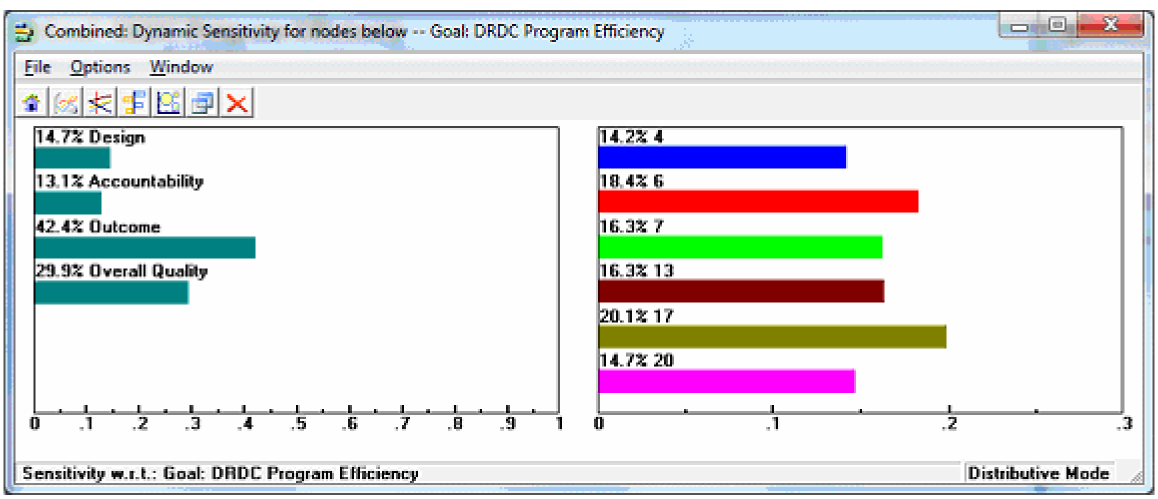


Figure 26. Sensitivity analysis, 'Overall quality' weight decrease for Cluster Group 1 (Source: Expert Choice, 2010)

The interest is in discovering whether minor changes in the input weights produce big effects in the group ranking compared to the original ranking of Figure 18. Table 28 summarizes the sensitivity analysis from the Figures 19 through 26 above.

Table 28. Summary of the AHP model sensitivity analysis with respect to criteria

Sub-criteria	**Minimum Weight**	**Original Weight**	**Maximum Weight**	**Shift (from Original to Rank Change)**
Design	0.103	0.134	0.358	-0.031 to +0.224
Accountability	0.000	0.120	0.541	-0.120 to +0.421
Outcome	0.217	0.387	0.413	-0.170 to +0.026
Overall quality	0.299	0.359	0.707	-0.060 to +0.348

The highlighted values in Table 28 denote the smallest shifts of criteria weight (less than 0.1) that result in changes to the Thrust rankings. The highest sensitivity in the above table is observed in criteria 'Outcome' with a 0.026 increase in weight, which is equal to a 7% change from the original weight of 0.387. Further detail and analysis should be developed to examine 'Outcome' more closely in order to justify the weights provided.

Analysis of the subcriteria

As shown in Figure 3, there are a total of 9 subcriteria in the hierarchy. 'Overall quality' was considered in the previous step as a main criterion and therefore 'Quality' which is its only subcriteria, is not part of the analysis at this stage. The same tool in *Expert Choice* is used for the subcriteria sensitivity analysis. Table 29 below shows the limits on subcriteria weights when a change in ranking takes place. Refer to Appendix N–"AHP Sensitivity Analysis for Subcriteria" for the graphs obtained from *Expert Choice* for the subcriteria sensitivity analysis.

Table 29. Summary of the AHP model sensitivity analysis with respect to sub-criteria

Sub-criteria	Minimum Weight	Original Weight	Maximum Weight	Shift (from Original to Rank Change)
Scope	0.000	0.218	0.787	-0.218 to +0.569
Hard Problems	0.093	0.603	1.000	-0.510 to +0.397
Originality	0.000	0.179	0.582	-0.179 to +0.403
Leverage	0.307	0.425	0.482	-0.118 to +0.057
Schedule Management	0.000	0.164	0.618	-0.164 to +0.454
Budget Management	0.348	0.411	0.514	-0.063 to +0.103
Exploitation Plan	0.475	0.500	1.000	-0.025 to +0.500
Potential for Uptake	0.000	0.500	0.525	-0.500 to +0.025

The highlighted values in Table 29 above denote those small shifts, high sensitive cases in criterion weights, before the original rankings are changed. The highest sensitivity in the above table is observed in 'Exploitation Plan' and 'Potential for Uptake'. The allowable 0.025 decrease/increase is equal to 5% change. The rest of the subcriteria display an allowable change of more than 25%.

4.3 Discussion of Results

In this section the LP model and AHP hierarchy results that were applied to the DRDC problem are discussed. Advantages and disadvantages of the methodologies are examined to determine their effectiveness and practicality in this application.

4.3.1 LP Result

The outcome of the LP method clearly points out the quantities of each resource to be allocated to the Thrusts. Quantities of different FTE types to each Thrust as well as the fund allocations are calculated proportional to the benefit function, taking into account the constraints. The advantage of LP lies within its ability to result in a direct quantitative value for resource allocation of FTEs and funding allocations to Thrusts.

However, the result of LP algorithm is heavily dependent on the extensive constraints set. The problem needs to be analyzed and all characteristics must be captured into the equations of constraints in order to obtain an accurate picture of the problem.

The concept of the benefit function in the LP model is not intuitive. The benefit function C_{ij} is calculated proportional to the transition function that brings FTE allocation from 2009-10 fiscal year to 2010-11. It is constructed based on scores, score weights and previous year's allocations. It mimics, based on driving parameters designed to reproduce actual allocations, the decisions made at DRDC for resource allocation and therefore leaves little room for redesign and modifications.

There is not a unique solution in the LP methodology. There exist multiple combinations of variables that can result to the same optimized function value. In reality some solutions can be deemed more practical than others due to the particular distribution of resources.

4.3.2 AHP Result

The Phase II output of the AHP method consists of 6 groups of Thrusts that are placed in order of performance. Within each group the Thrusts are ranked and a score for each is provided with respect to the main objective, DRDC program efficiency.

An important effort in AHP is organizing the problem in a hierarchy. This exercise helps decision makers obtain a clearer picture of the problem. Implementing the hierarchy in the AHP methodology is considered an art as well as a science. Therefore its quality increases with more practice within the organization.

The pairwise comparison is another advantage as it allows the decision makers to concentrate on a small and manageable portion of the problem and leave the synthesis of all these judgements to the algorithm. The questionnaire that was distributed between the decision makers was not time consuming or difficult to produce as was described as a drawback by Qureshi and Harrison (2003). However as the complexity of the hierarchy increases, both questionnaire length and time required to interview stakeholders can be cumbersome. The annual nature of this process at DRDC reduces the importance of this aspect of AHP methodology.

Expert Choice also accommodates group decision making. The comparison values by each user are entered into the software and *Expert Choice* aggregates the decisions into one set of weights for criteria. These weights are used to rank further the alternatives in the DRDC problem. Decision maker participants can also be taken from various groups that do not necessarily have the same priority. Therefore, the final result is the output of considering various viewpoints toward the overall criteria.

The result of the AHP method presented in ranked Thrusts does not specify the exact allocation of FTEs like the LP algorithm does. To further apply the weights of Thrusts to obtain the FTE distribution, another algorithm is applied. There are decisions that need to be taken on how to deal with scarce resources. In the AHP resource allocation, it was assumed that a different FTE type can substitute. Also the substitute is selected among the least favoured of the lower ranked Thrust groups.

One of the advantages of the AHP resource allocation over LP is that the resources are distributed proportional to a rating. Therefore the value is always somewhere between the upper bound (what the Thrusts have asked for) and the minimum set by DRDC management. In LP, most answers are pushed either to the max (because of higher benefit value), or placed at the minimum. This increases the risk of managing projects as they may fail due to unavailability of certain resources, while other projects are enjoying an abundance of FTEs.

5 Conclusions and Future Research

This section summarizes the conclusion of the AHP and LP results as modelling approaches for the structuring of the DRDC S&T program's evaluation. It also discusses recommendations for future research.

5.1 Conclusions

The first objective of this research is to formulate the annual planning process into a model that captures all of the problem's salient characteristics. The second objective is to develop an applied evaluative method to improve DRDC's S&T program allocation structure. And finally, the third objective is to provide a framework to implement and test the model.

(1) Applying the two methods to formulate DRDC's problem showed that AHP captures its features best. The flexibility of AHP in displaying the network of criteria and objectives promotes better understanding of the problem. It provides the ability to approach criteria and subcriteria individually at a lower and manageable scale. Also changes in the structure of the problem are implemented easier in AHP than in LP. The graphical representation of the hierarchy could accommodate a partial redesign of the problem very well.

(2) The second objective is to build a model in order to optimize DRDC's resources. This is accomplished by ranking the solution set in AHP. The output of AHP is ranked Thrusts with pertinent priority. This can determine what portion of the resources will be allocated to each Thrust. However, this needs to be further translated into assigning various resources to each project, which was demonstrated in section 4.2.2. The LP model is built by implementing the benefit function which was estimated from resource reallocation from fiscal years 2009-2010 and 2010-2011.

(3) The third objective is to implement and test the models. Both AHP and LP models were applied to the CPME data from DRDC and where also examined through sensitivity analyses. The value of the objective function in the LP model is analyzed in different scenarios involving the constraints and in comparison with actual 2010-2011 resource allocation (Appendix G – LP Results Analysis). Results of the AHP model are also analyzed for sensitivity and the AHP rankings and weights are applied to allocate resources to Thrusts. It demonstrates that the AHP model captures the current process well for program prioritisation at DRDC.

One of the interesting concepts that were applied to the Thrusts prior to our AHP methodology was clustering. This arranges the Thrusts that are similar into clusters, and helps the decision makers to preserve diversity in DRDC's portfolio. The best Thrusts in each group are awarded a bigger portion of resources than the following ranked Thrust from each group. It will distribute the resources between Thrusts that are doing best and have varied characteristics. This method will dictate the resource allocation to each Thrust based on its performance. Previously the PGs were awarded almost the same amount every year. This now makes the PGs competitive as the total resource allocation to each PG can be noticeably different depending on the performance of their individual Thrusts.

The LP algorithm on the other hand lacks the flexibility of the AHP approach. Changes to the LP model to smooth out the inconsistencies require elaborate and careful redesign of the system. The whole picture of the model is not intuitively evident from the set of equations, whereas most of the AHP methodology can be explained by its hierarchy. AHP's visual design alleviates the severity of required steps to implement changes. Therefore AHP provides easier means of implementing revisions to the model in future if such changes are deemed necessary. The use of the AHP methodology resulted in a framework that is simple, traceable and rigorous in the creation of a strategic plan.

From the analysis discussed, it can be concluded that AHP methodology and the demonstrated structuring for resource allocation using AHP's ranking, is the preferred model for the DRDC program prioritisation. AHP demonstrated a process where multiple players at different levels can participate. The hierarchy and related procedures accommodate change easily and are intuitive, whereas the LP solution requires familiarity and knowledge of the complex relationships of the LP model elements. Also LP allocations in most cases assign resources in upper or lower bounds which it can result in higher risk in project management as minimal resources can be problematic. AHP however, distributes the risk between each Thrust group and not individual Thrusts.

5.2 Future Research

This section discusses the opportunities to further examine certain aspect of this research. Some are related to improvements to a particular portion of the computations and some discuss possible enhancement to the algorithms.

(1) **Review of Clustering**. The fundamental concept of clustering could be revisited and improved to guarantee better diversification of Thrusts. The aim is to reduce the amount of human interaction with the outcome of k-means algorithm to further optimize clustering. This will eliminate the possibility of biased decisions influencing this crucial step. Moreover the variables that are used for clustering in this thesis were based on the availability of information through DRDC database, CPME. A study can be conducted to determine if more descriptive and appropriate variables exist to be used in the clustering algorithm.

(2) **Phase II Grouping** - AHP methodology in DRDC problem can be implemented at a larger scale to include more individuals and open ways for discussions within DRDC for selecting criteria and refining the problem structure. The way the subcriteria are grouped together and the terminologies selected for the criteria can be modified to better convey

the subcriteria it entails, accommodating the comparisons by participants in pairwise comparison sessions.

(3) **Multi-participant Inclusion**. One of the assumptions in this thesis was that all decision makers have the same weight when providing their pairwise comparisons. However the reality can be different. For variety of reasons decision makers can be from multiple levels of management that do not necessarily have the same experience, knowledge and expectations. If deemed appropriate, a weighting scheme can be associated in the computations.

(4) **Linear Programming Datasets**. Computation of the benefit function C_{ij}, could be improved through Non-Linear Programming (NLP). The logic behind C_{ij} calculation was to compute the score weights so that the framework produces results similar to the 2010-2011 FTE assignment. This requires the algorithm to minimize the distance between the produced output and the actual 2010-11 FTE allocation. Minimizing this distance introduces absolute value computations which in turn results in non-linearity of the system.

6 Bibliography

Anderson, D., Sweeney, D. and Williams, T. 1995. Quantitative Methods for Business. St. Paul, Minn.: West Publishing Company.

Anderson, D., Sweeney, D. and Williams, T. 2004. The Management Scientist, v6.0 2e, Published by Cengage Learning.

Bajalinov, E.B. 2003. Linear-Fractional Programming: Theory, Methods, Applications and Software. Boston: Kluwer Academic Publishers

Basu, S., Davidson, I. and Wagstaff, K.L. 2009. Constrained Clustering. CRC Press. Taylor & Francis Group. Boca Raton, London, New York.

Belton, V. and Gear, T. 1983. On a Short-coming of Saaty's Method of Analytic Hierarchies. Omega, 11, 3, 228-230.

Berenson, M.L., Levine, D.M. and Rindskopf, D. 1988. Applied Statistics. Prentice Hall, Englewood Cliffs, New Jersey.

Betsch, T. and Haberstroh, S. 2005, The Routines Of Decision Making. Lawrence Erlbaum Associates.

Bhushan, N. and Rai, K. 2004. Strategic Decision Making. Springer.

Boender, C. G. E., De Graan, J. G. and Lootsma, F. A. 1989. Multi-Criteria decision Analysis with Fuzzy Pairwise Comparisons. Fuzzy Sets and Systems, 29, 133-143.

Bouyssou, D., Marchant, T., Pirlot, M., Perny, P., Tsoukias, A. and Vincke, P. 2000. Evaluation and decision models. Kluwer Academic Publishers.

Buchanan, J. and Sheppard, P. 1999. Project ranking using ELECTRE III. University of Waikato, New Zealand.

Bunn, D.W. 1982. Analysis for Optimal Decisions. John Wiley & Sons.

COOPR, 2012. Sandia National Laboratories, https://software.sandia.gov/trac/coopr accessed April 2012.

Coyle, G. 2004. THE Analytic Hierarchy Process (AHP). Practical Strategy. Pearson Education Limited.

Dantzig, G.B. 1968. Linear Programming and Extensions. Princeton University Press.

Dantzig, G.B. and Thapa M.N. 2003. Linear Programming, Theory and Extensions. Springer.

Darst, R.B. 1991. Introduction to Linear Programming. Marcel Dekker, Inc.

Davies, D.L. and Bouldin, D.W. 1979. "A cluster separation measure", IEEE transactions on pattern analysis and machine intelligence, 1, 2, 95-104.

Decision Deck, 2013. http://www.decision-deck.org, accessed March 2013.

DRDC, 2010a. Annual report for the year ending 31 March 2010.

DRDC, 2010b. Functional Planning Guidance. Assistant Deputy Minister (Science and Technology), Defence Research and Development Canada.

DRDC CORA, 2010. http://www.cora.drdc-rddc.gc.ca, accessed November 2010.

DRDC, 2011a. http://www.drdc-rddc.gc.ca, accessed January 2011

DRDC, 2011b. Collaborative Planning and Management Environment (CPME). Dataset of projects in DRDC.

Davies, M. 2001. Adaptive AHP: a review of marketing applications with extensions. European Journal of Marketing, 35, 7/8, pp. 872-893.

Dezert, J. and Tacnet, J.M. 2012. Soft ELECTRE TRI outranking method based on belief functions. Fusion 2012 – 15th International conference on Information Fusion. Singapour, 2012.

Eiselt H.A. and Sandblom, C.L. 2007. Liner Programming and its Applications. Springer.

Emond, E.J. 2006. Development in the Analysis of Rankings in Operational Research. DRDC CORA TR 2006-37. Technical report, Defence R&D Canada, Centre for Operational Research and Analysis. December, 2006.

Expert Choice, 2011. http://www.expertchoice.com, accessed April 2011.

Figueira, J., Greco, S., Slowinski, R., 2009. Building a set of additive value functions representing a reference preorder and intensities of preference: GRIP method. European Journal of Operational Research, 195, 460-486, 2009.

Forman, E. and Shelly, M.A. 2001. Decision by Objectives: How to convince others that you are right. World Scientific Publishing Company, New York.

Fui, K.Y. and Sheng, L.H. 2011. Using Analytic Hierarchy Process with Operations Analysis in Project Evaluation. DSTA Horizons. Defence Science & Technology Agency, Singapore. 135-143.

GNU Project, 2013. http://www.gnu.org/software/glpk, accessed March 2013.

Goodwin, P. and Wright, G. 2004. Decision Analysis for Management Judgment. John Wiley & Sons, Ltd.

Hartigan, J.A. 1975. Clustering Algorithms. John Wiley & Sons. New York, London, Sydney, Toronto.

Govaert, G. 2009. Data Analysis. Willey, Hoboken NJ and ISTE, London UK.

Hobbs, B.F. and Meier, P. 2000. Energy Decisions and the Environment. Kluwer Academic Publishers, Boston.

Holland, S.M. 2008. Principal Components Analysis (PCA). Department of Geology, University of Georgia.

JOptimizer, 2012. http://www.joptimizer.com, accessed March 2012.

Kendall, M. 1938. A new measure of rank correlation. Biometrica, 30(1–2) pp.81–89.

Krawetz, S.A. 2009. Bioinformatics for systems biology. Springer.

Land, A. H. and Doig , A. G. 1960. An automatic method of solving discrete programming problems. Econometrica 28 (3): pp. 497-520.

Lane, D.E. 2007. Planning in Fisheries-Related Systems. Handbook of Operations Research in Natural Resources. Springer. Chapter 13.

Levin,R.I. 1987. Statistics for Management. Englewood Cliffs, N.J Prentice-Hall.

Lindo Systems, 2011. http://www.lindo.com, accessed April 2011

Mahmoodzadeh, S., Shahrabi, J., Pariazar, M. and Zaeri, M.S. 2007. Project Selection by Using Fuzzy AHP and TOPSIS Technique. International Journal of Human and social sciences, 1, 59-66.

Mallach, E.G. 1994. Understanding Decision Support Systems and Expert Systems. Irwin.

Mansini, R. 2003. On LP Solvable Models for Portfolio Selection. Informatica Vol. 14. Institute of Mathematics and Informatics, Vilnius.

Martinez, A.M. and Kak, A.C. 2001. PCA versus LDA. IEEE transactions on pattern analysis and machine intelligence, 23, 2.

Murad, H. and Javaid L.P. 2007. Analytic Network Process Applied to R&D Project Selection.

Mogharreban, N. 2006. Adaptation of a Cluster Discovery Technique to a Decision Support System. Interdisciplinary Journal of Information, Knowledge, and Management, 1, p59-68.

Mohammadi, A. Mohammadi, A. Mohammadi, M. and Mohammadi, A. 2011. ELECTRE Decision Making Method with Triangular Fuzzy Numbers. Australian Journal of Basic and Applied Sciences, 5, 12, pp. 1180-1189.

Pedrycz, W. Ekel, P. Parreiras, R. 2011. Fuzzy Multicriteria Decision-Making, Models, Methods and Applications. Wiley.

Phillips-Wren, G. Hahn, E. Forgionne, G. 2008. Consensus Building in Collaborative Decision Making. Collaborative Decision Making: Perspectives and Challenges. IOS Press.

Pollard, D. 1981. Strong consistency of k-Means clustering. The Annals of Statistics, 9, 1. Institute of Mathematical Statistics.

OpenOpt, 2011. http://openopt.org, accessed January 2011.

Qureshi, M.E. and Harrison, S.R. 2003. Application of the Analytic Hierarchy Process to Riparian Revegetation Policy Options. Small-scale Forest Economics, Management and Policy, 2, 3, 441-458

Raczynski, C.M. 2008. A methodology for comprehensive strategic planning and program prioritization. Georgia Institute of Technology.

Ragsdale, C.T. 2001. Spreadsheet Modeling and Decision Analysis. South-western college publishing.

Ray, S. and Turi R.H. 2000. Determination of Number of Clusters in K-Means Clustering and Application in Colour Image Segmentation. School of Computer Science and Software Engineering. Clayton, Victoria, Australia.

Roy, B. 1968. Classement et choix en présence de critères multiples (la méthode ELECTRE), RIRO, 8, 57-75.

R Project, 2012. http://www.r-project.org, accessed February 2012.

Saaty, T. L. 1980. The Analytic Hierarchy Process: Planning, priority setting, resource allocation. McGraw-Hill, New York.

Saaty, T.L. 2001. Fundamentals of the Analytic Hierarchy Process. The Analytic Hierarchy Process in Natural Resource and Environmental Decision Making. Kluwer Academic Publishers. Chapter 2.

Saaty, T. L. and Vargas, L. G. 2006. Decision Making with the Analytic Network Process. Springer

Saaty, T. L. 2008. Decision making with the analytic hierarchy process. International Journal of Services Sciences, Vol. 1, No. 1.

Saari, D.G. 1999. Explaining All Three-Alternative Voting Outcomes. Journal of Economic Theory, 87, 313-355.

Schmoldt, D.L., Kangas, J. Mendoza, G.A. 2001. Basic principles of decision making in natural resources and environment. The Analytil Hierarchy Process in Natural Resource and Environmental Decision Making. Chapter 1.

Shapiro, S.S. and Wilk, M.B. 1965. An analysis of variance test for normality. Biometrika, 52, 3/4. 591-611.

Simon, H.A. 1960. The New Science of Decision Making. Harper & Row, New York.

Simonnard, M. 1966. Linear Programming. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Slowinski, R. 2010. Robust Ordinal Regression Approach to Multiple Criteria Decision Aiding. MCDA Summer School, Poznan University of Technology, Paris 2010.

Stevenson, W. 2010. Introduction to Management Science. McGraw-Hill.

Tayebi, N. 2010. Identification and Characterization of a Cost-Effective Combination of Systems for Arctic Surveillance: The Northern Watch Project. University of Ottawa.

Triantaphyllou, E. 2000. Multi-Criteria Decision Making Methods: A Comparative Study. Kluwer Academic Publishers, Dordrecht.

Triantaphyllou, E., Mann, S.H. 1995. Using the Analytic Hierarchy Process for Decision Making in Engineering Applications. Journal of Industrial Engineering, 2, 1, 35-44.

Triantaphyllou, E., Shu, B., Nieto Sanchez, S. and Ray, T. 1998. Multi-Criteria Decision Making: An Operations Research Approach. Encyclopedia of Electrical and Electronics Engineering, Vol 15. John Wiley & Sons, New York, NY.

Young, H.P. 1988. Condorcet's Theory of Voting. The American Political Science Review, 82, 4, p1231-1244.

Young, P. 1995. Optimal Voting Rules. Journal of Economic Perspectives, 9, 1, 51-64.

Van Laarhoven, P. J. M. and Pedrycz, W. 1983. "A Fuzzy extension of Saaty's Priority Theory," Fuzzy Sets and Systems, 11, 229-241.

Wang, H. and Song, M. 2011. Optimal k-means Clustering in One Dimension by Dynamic Programming. The R Journal, 3, 2, 29-33.

Wardoyo, R. Hartati, S. and Harjoko, A. 2012. ELECTRE-Entropy method in Group Decision Support System Modelto Gene Mutation Detection. International Journal of Advanced Research in Artificial Intelligence, Vol. 1, No. 1, 2012.

Warren, L. 2004. Uncertainties in the Analytic Hierarchy Process. DSTO-TN-0597. Defence Science and Technology Organization, Australia. http://handle.dtic.mil/100.2/ADA431022 (Accessed on November 2010)

Weiss, N.A. 1999. Elementary Statistics. Addison-Wesley.

Wheaton, K.R. and Bayly, M. 2010. S&T Program Synopsis 2010-2013, DRDC Internal Paper, November 2010.

Zielniewicz, P. Figueira, J.R, Greco, S. and Slowinski, R. 2008. GRIP: an MCDA method using a set of additive value functions representing a reference preorderand intensities of preference. European Working Group "Multiple Criteria Decision Aiding". Vol. 3, No. 18, 2008.

Appendix A – CPME Data Analysis

This appendix contains Thrust scores calculated by 3 different methods: arithmetic mean, median and mode. The scores are displayed in tables followed by graphs for Thrusts' relative ranking. To produce the graphs, arithmetic mean is used across the Thrust scores to derive a single score value for each Thrust. Equal weights for criteria are considered in Thrust score calculations.

Two averages are being calculated here. First, the average of scores for each criterion within a Thrust is computed (rows of Table A1). Then arithmetic mean is used to produce an average of each row, resulting in a single value for each Thrust (Figure A1). This procedure is followed for arithmetic mean, median and mode, and for both fiscal years 2009-2010 and 2010-2011.

Table A1. Arithmetic mean of project scores within each Thrust for fiscal year 2009-2010

Thrust	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverag e DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
1	4.44	3.78	1.67	3.33	1.78	3.78	3.00	5.00	3.67
2	4.00	3.93	2.06	3.53	0.07	3.73	3.07	4.07	3.73
3	4.00	3.75	1.43	3.17	0.00	3.83	3.83	4.58	3.25
4	3.90	3.40	0.83	3.10	0.00	3.60	4.20	5.00	3.00
5	3.29	3.43	0.00	3.00	0.00	3.43	3.29	4.86	2.86
6	3.63	3.63	2.37	3.94	0.00	3.38	3.19	4.63	3.25
7	2.60	3.20	2.27	3.80	0.00	3.70	3.00	4.80	2.80
8	3.33	3.83	2.14	2.67	0.00	3.83	4.50	5.00	3.17
9	4.67	3.00	0.00	4.67	0.33	3.67	3.67	5.00	3.33
10	3.43	4.14	0.56	3.29	0.21	4.71	4.57	4.71	2.71
11	3.86	4.00	1.54	3.43	0.00	4.14	4.14	5.00	2.57
12	3.78	3.56	2.69	3.89	0.00	4.00	4.11	4.86	2.67
13	4.11	3.89	1.32	3.39	0.01	3.94	4.22	4.39	3.28
14	3.78	3.89	2.27	3.11	0.00	3.71	3.56	4.89	2.56
15	3.75	3.50	3.75	3.75	0.00	3.75	4.25	5.00	3.50
16	4.00	4.00	2.27	3.40	0.00	3.60	3.70	4.80	2.90
17	3.91	3.73	2.73	3.73	0.00	3.80	3.91	4.82	3.55
18	3.00	3.67	5.00	2.67	0.00	4.33	3.83	4.17	2.50
19	3.13	3.38	5.00	2.50	0.00	4.13	4.38	5.00	2.38
20	3.25	3.50	2.22	2.38	0.00	3.29	3.50	4.25	3.00
21	4.00	3.00	3.33	3.60	0.40	4.00	3.60	5.00	2.80

22	4.50	3.88	5.00	4.50	2.76	3.88	4.00	4.88	4.13
23	3.50	3.25	5.00	4.25	2.31	3.75	4.00	5.00	3.75
24	2.90	3.50	5.00	3.60	1.50	3.00	4.20	5.00	3.00
25	3.00	3.10	0.45	2.10	0.14	2.83	4.40	5.00	3.00
26	3.86	3.64	2.33	2.43	0.00	4.07	4.57	4.71	3.21
27	4.00	3.88	0.56	2.75	0.25	3.63	3.25	4.63	3.38
28	4.43	4.14	1.11	2.43	0.00	2.57	4.00	5.00	3.14
29	3.50	3.75	2.31	2.50	0.29	4.50	2.88	4.88	3.00
30	3.82	4.00	2.14	3.55	0.00	3.91	3.45	4.45	3.45

The values above are used to compute a single Thrust score as displayed in Figure A1. Equal weights are assigned to the criteria in the single score calculations.

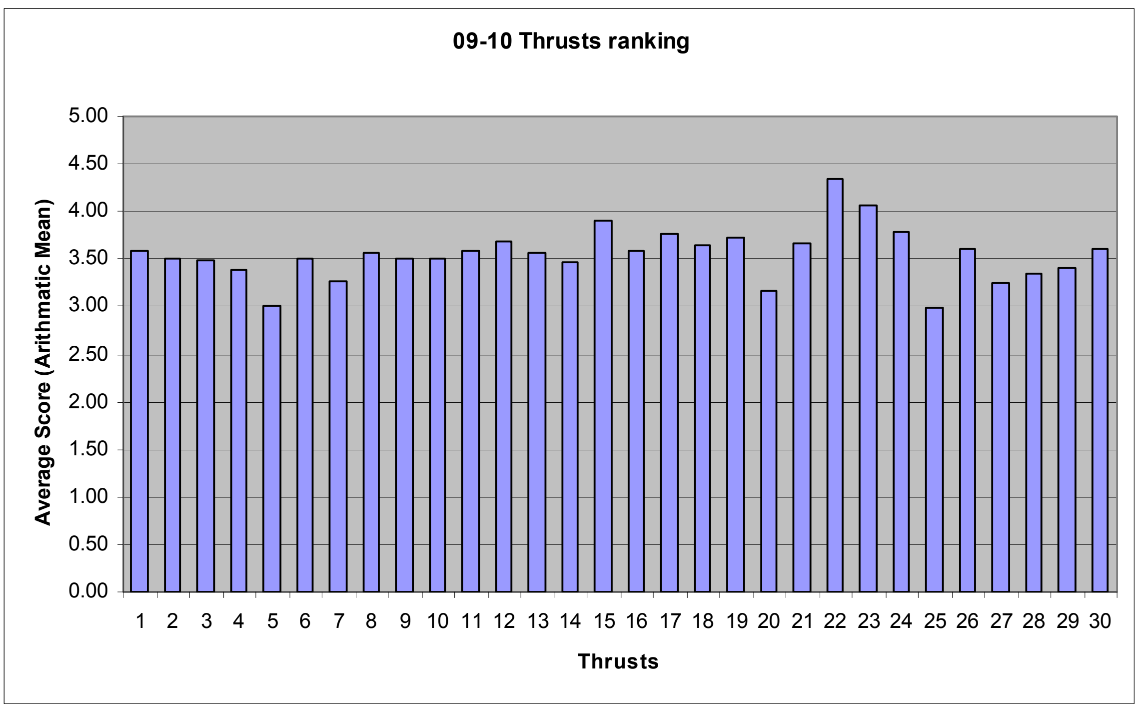


Figure A1. Thrust scores computed by arithmetic mean 2009-2010

Table A2 below, contains the average score for each Thrust in fiscal year 2009-2010. The average values are calculated by median of the project scores in each Thrust.

Table A2. Median of project scores within each Thrust for fiscal year 2009-2010

Thrust	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
1	4.00	1.67	3.00	3.00	4.00	4.00	3.00	5.00	4.00
2	4.00	2.06	4.00	3.00	4.00	4.00	3.00	4.00	4.00
3	4.00	1.43	3.50	4.00	4.00	4.00	4.00	5.00	3.00
4	3.00	0.83	3.00	4.00	4.00	3.50	4.00	5.00	3.00
5	3.00	0.00	2.00	2.00	3.00	3.00	4.00	5.00	3.00
6	4.00	2.37	4.00	4.00	3.00	3.00	3.00	5.00	3.00
7	3.00	2.27	3.50	3.00	2.50	4.00	3.00	5.00	3.00
8	4.00	2.14	2.50	1.50	3.00	4.00	4.50	5.00	3.00
9	3.00	0.00	5.00	1.00	5.00	3.00	3.00	5.00	3.00
10	4.00	0.56	3.00	3.00	3.00	5.00	5.00	5.00	3.00
11	4.00	1.54	3.00	4.00	4.00	4.00	4.00	5.00	3.00
12	3.00	2.69	4.00	2.00	4.00	4.00	5.00	5.00	2.00
13	4.00	1.32	3.00	4.00	4.00	4.00	4.00	4.00	3.00
14	4.00	2.27	3.00	3.00	4.00	4.00	4.00	5.00	2.00
15	3.50	3.75	3.50	3.00	4.00	4.00	4.00	5.00	3.50
16	4.00	2.27	3.50	3.00	4.00	4.00	4.00	5.00	3.00
17	4.00	2.73	4.00	4.00	4.00	4.00	4.00	5.00	3.00
18	4.00	5.00	3.00	3.00	3.00	5.00	5.00	4.50	2.50
19	3.00	5.00	2.50	4.00	3.00	4.00	5.00	5.00	2.00
20	3.50	2.22	2.50	3.00	3.50	3.00	4.00	4.00	3.00
21	3.00	3.33	3.00	4.00	4.00	4.00	3.00	5.00	3.00
22	3.50	5.00	4.50	3.50	4.50	4.00	4.00	5.00	4.00
23	3.50	5.00	4.50	3.00	3.50	4.00	4.00	5.00	3.50
24	3.50	5.00	3.00	4.00	3.00	3.00	4.00	5.00	3.00
25	3.00	0.45	2.00	2.00	3.00	3.00	4.00	5.00	3.00
26	4.00	2.33	2.00	5.00	4.00	4.00	5.00	5.00	3.00
27	4.00	0.56	2.50	2.50	4.00	4.00	3.00	5.00	3.00
28	4.00	1.11	2.00	2.00	4.00	2.00	4.00	5.00	3.00
29	4.00	2.31	2.00	4.50	3.50	5.00	3.00	5.00	3.00
30	4.00	2.14	3.00	5.00	4.00	4.00	4.00	5.00	4.00

The values above are used to compute a single Thrust score as displayed in Figure A2. Equal weights are assigned to the criteria in the single score calculations.

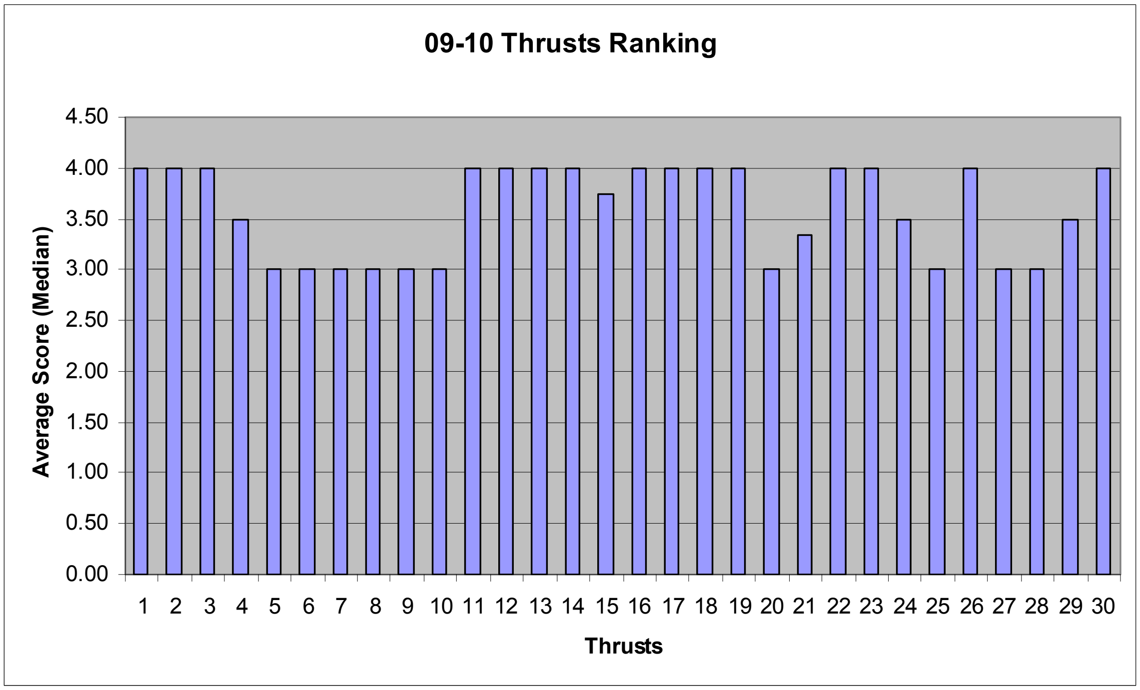


Figure A2. Thrust scores computed by median 2009-2010.

Table A3 below, contains the average score for each Thrust in fiscal year 2009-2010. The average values are calculated by Mode of the project scores in each Thrust.

Table A3. Mode of project scores within each Thrust for fiscal year 2009-2010.

Thrust	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
1	4.00	1.67	3.00	3.00	4.00	5.00	3.00	5.00	4.00
2	4.00	2.06	4.00	3.00	5.00	4.00	3.00	5.00	4.00
3	3.00	1.43	4.00	5.00	4.00	4.00	4.00	5.00	3.00
4	3.00	0.83	2.00	5.00	4.00	5.00	5.00	5.00	3.00
5	3.00	0.00	2.00	1.00	3.00	3.00	4.00	5.00	3.00
6	4.00	2.37	5.00	5.00	3.00	3.00	3.00	5.00	3.00
7	3.00	2.27	3.00	5.00	4.00	4.00	3.00	5.00	3.00
8	5.00	2.14	2.00	1.00	3.00	5.00	4.00	5.00	3.00
9	3.00	0.00	5.00	1.00	5.00	3.00	3.00	5.00	3.00
10	4.00	0.56	3.00	3.00	3.00	5.00	5.00	5.00	3.00
11	4.00	1.54	3.00	4.00	4.00	4.00	4.00	5.00	3.00
12	3.00	2.69	5.00	1.00	4.00	5.00	5.00	5.00	2.00
13	4.00	1.32	3.00	4.00	4.00	4.00	4.00	4.00	3.00
14	4.00	2.27	2.00	3.00	4.00	4.00	4.00	5.00	2.00
15	4.00	3.75	3.00	4.00	4.00	4.00	4.00	5.00	4.00
16	4.00	2.27	4.00	3.00	4.00	4.00	4.00	5.00	3.00
17	4.00	2.73	4.00	4.00	4.00	4.00	4.00	5.00	3.00
18	4.00	5.00	3.00	3.00	4.00	5.00	5.00	5.00	3.00
19	3.00	5.00	3.00	4.00	3.00	4.00	5.00	5.00	2.00
20	3.00	2.22	1.00	3.00	4.00	3.00	4.00	4.00	3.00
21	3.00	3.33	3.00	4.00	4.00	4.00	3.00	5.00	3.00
22	3.00	5.00	4.00	4.00	5.00	4.00	4.00	5.00	5.00
23	4.00	5.00	5.00	2.00	3.50	4.00	4.00	5.00	3.00
24	4.00	5.00	3.00	4.00	2.00	4.00	4.00	5.00	3.00
25	4.00	0.45	2.00	1.00	3.00	4.00	4.00	5.00	3.00
26	4.00	2.33	2.00	5.00	4.00	4.00	5.00	5.00	3.00
27	4.00	0.56	2.00	2.00	4.00	4.00	3.00	5.00	3.00
28	4.00	1.11	2.00	2.00	4.00	2.00	4.00	5.00	4.00
29	4.00	2.31	2.00	5.00	4.00	5.00	2.00	5.00	4.00
30	4.00	2.14	3.00	5.00	4.00	4.00	4.00	5.00	4.00

The values above are used to compute a single Thrust score as displayed in Figure A3. Equal weights are assigned to the criteria in the single score calculations.

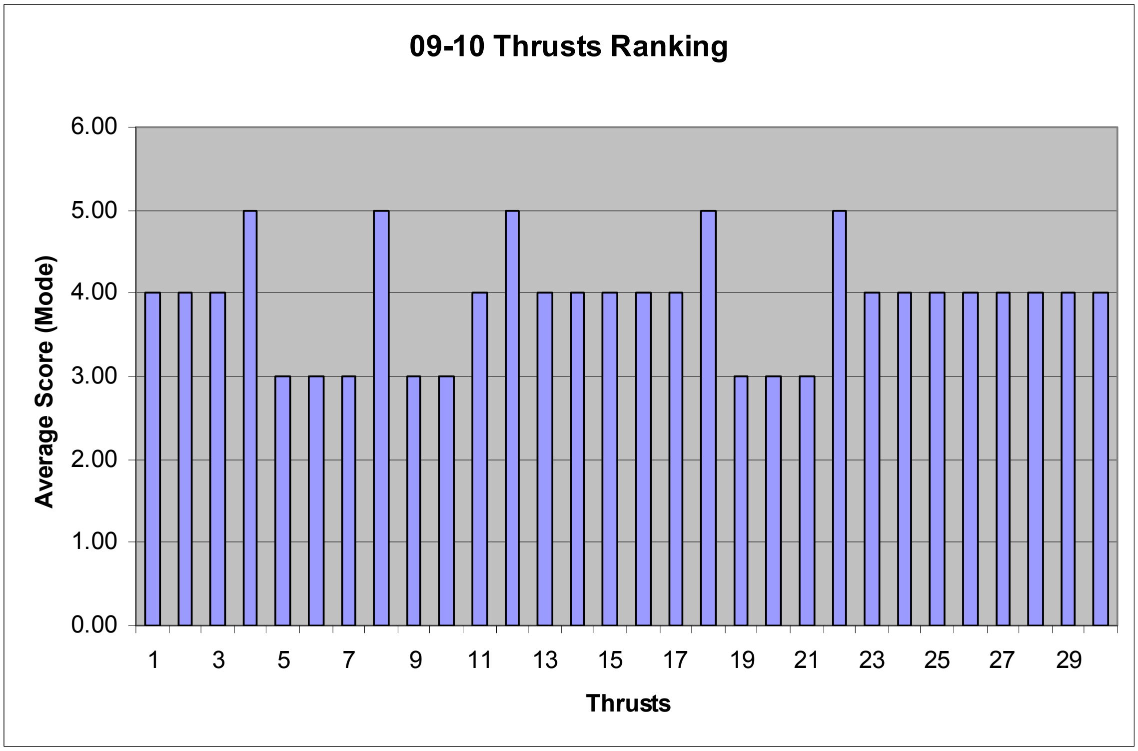


Figure A3. Thrust scores computed by mode 2009-2010.

Table A4 below, contains the average score for each Thrust in fiscal year 2010-2011. The average values are calculated by arithmetic mean of the project scores in each Thrust.

Table A4. Arithmetic mean of project scores within each Thrust for fiscal year 2010-2011

Thrust	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverag e DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
1	4.44	3.78	1.67	3.33	3.44	3.78	3.00	5.00	3.67
2	4.00	3.93	2.33	3.53	2.80	3.73	3.07	4.07	3.60
3	4.00	3.83	1.00	3.17	3.33	3.83	4.00	4.25	3.25
4	3.90	3.40	0.83	3.10	3.30	3.80	5.00	5.00	2.90
5	3.29	3.43	0.00	3.00	2.14	3.14	4.86	4.86	2.57
6	3.69	3.75	2.22	4.06	3.63	3.06	4.56	4.31	2.94
7	2.90	3.20	2.08	3.90	3.20	3.40	4.30	4.80	2.80
8	3.33	3.83	2.50	2.67	2.00	4.00	4.00	5.00	3.67
9	4.67	3.00	0.00	4.67	1.33	3.00	4.67	5.00	3.00
10	3.43	3.71	0.63	3.29	2.71	5.00	5.00	5.00	3.14
11	3.86	4.00	1.25	3.43	3.57	4.14	4.14	5.00	2.57
12	3.78	3.67	1.92	3.89	2.00	4.00	4.11	3.78	2.78
13	4.11	3.89	1.32	3.50	4.28	3.94	4.22	4.39	3.33
14	3.89	4.00	2.08	3.11	3.11	4.00	4.56	4.89	4.11
15	3.75	3.50	2.00	3.75	2.75	3.75	4.25	5.00	3.50
16	4.00	4.00	2.27	3.40	3.40	3.60	3.70	4.80	2.90
17	3.91	3.73	2.50	3.73	4.45	3.80	3.91	4.82	3.55
18	2.83	3.50	3.75	2.33	3.50	4.00	3.83	4.17	2.83
19	3.13	3.38	5.00	2.50	4.00	4.13	4.38	5.00	2.38
20	3.25	3.25	2.78	2.25	3.13	3.00	3.50	4.00	2.75
21	4.00	3.00	2.50	3.60	3.60	4.00	3.60	5.00	2.80
22	4.50	3.88	4.44	4.50	3.38	3.88	4.00	4.88	4.13
23	3.50	3.25	4.00	4.50	3.25	4.00	4.00	5.00	3.75
24	2.90	3.50	4.55	3.60	3.70	3.00	4.20	5.00	3.00
25	3.00	3.10	0.33	2.10	2.30	2.83	4.40	4.50	3.00
26	3.86	3.79	1.58	2.43	3.86	4.07	4.57	4.71	3.21
27	3.75	3.88	0.56	2.63	2.63	3.63	3.25	4.63	3.00
28	4.43	4.14	0.42	2.43	2.57	2.71	4.00	5.00	3.29
29	3.50	3.75	1.25	2.50	4.13	4.25	2.63	4.88	2.88
30	3.91	3.91	1.67	3.45	4.09	3.73	3.18	4.64	3.36

The values above are used to compute a single Thrust score as displayed in Figure A4. Equal weights are assigned to the criteria in the single score calculations.

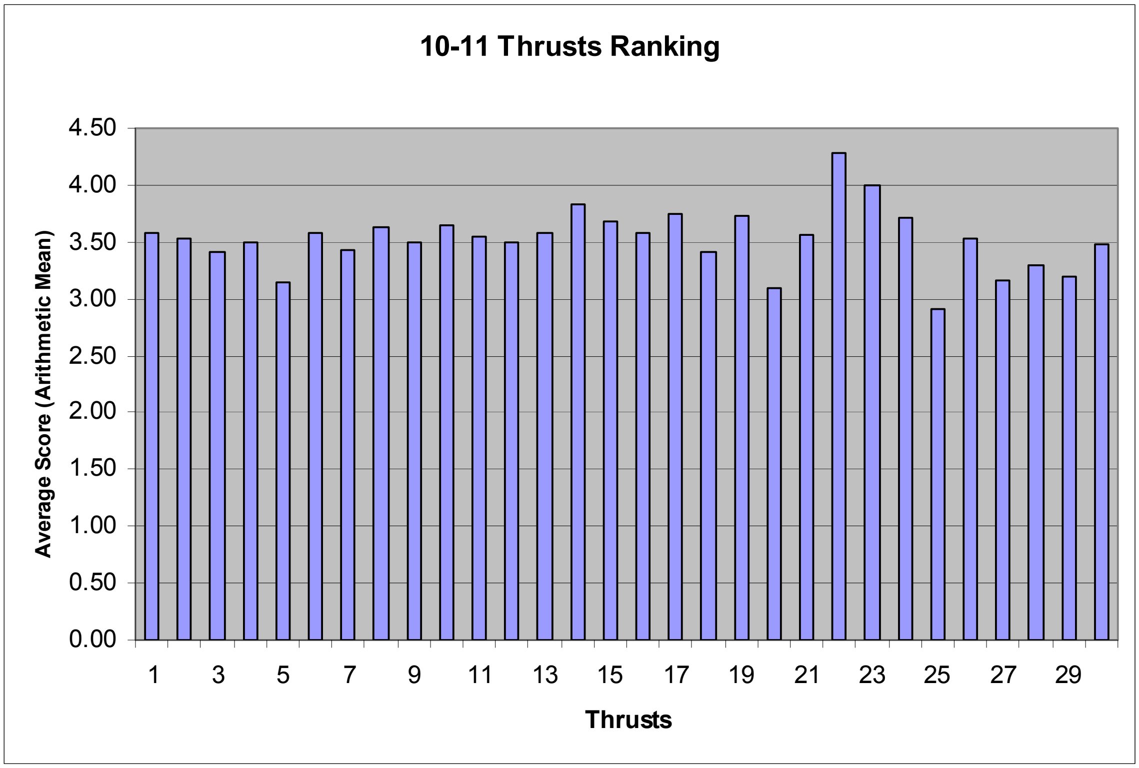


Figure A4. Thrust scores computed by arithmetic mean 2010-2011.

Table A5 below, contains the average score for each Thrust in fiscal year 2010-2011. The average values are calculated by median of the project scores in each Thrust.

Table A5. Median of project scores within each Thrust for fiscal year 2010-2011

Thrust	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
1	4.00	4.00	1.67	3.00	3.00	4.00	3.00	5.00	4.00
2	4.00	4.00	2.33	4.00	3.00	4.00	3.00	4.00	4.00
3	4.00	4.00	1.00	3.50	4.00	4.00	4.00	5.00	3.00
4	4.00	3.00	0.83	3.00	4.00	4.00	5.00	5.00	3.00
5	3.00	3.00	0.00	2.00	2.00	3.00	5.00	5.00	3.00
6	3.50	4.00	2.22	4.00	4.00	3.00	5.00	5.00	3.00
7	3.00	3.00	2.08	4.00	3.00	3.00	4.50	5.00	2.00
8	3.00	4.00	2.50	2.50	1.50	4.00	5.00	5.00	4.00
9	5.00	3.00	0.00	5.00	1.00	3.00	5.00	5.00	3.00
10	3.00	4.00	0.63	3.00	3.00	5.00	5.00	5.00	3.00
11	4.00	4.00	1.25	3.00	4.00	4.00	4.00	5.00	3.00
12	4.00	4.00	1.92	4.00	2.00	4.00	5.00	5.00	3.00
13	4.00	4.00	1.32	3.00	4.00	4.00	4.00	4.00	3.00
14	4.00	4.00	2.08	3.00	3.00	4.00	5.00	5.00	4.00
15	4.00	3.50	2.00	3.50	3.00	4.00	4.00	5.00	3.50
16	4.00	4.00	2.27	3.50	3.00	4.00	4.00	5.00	3.00
17	4.00	4.00	2.50	4.00	4.00	4.00	4.00	5.00	3.00
18	2.50	3.50	3.75	2.50	3.00	4.50	5.00	4.50	3.00
19	3.00	3.00	5.00	2.50	4.00	4.00	5.00	5.00	2.00
20	3.50	3.00	2.78	2.50	3.00	3.00	4.00	4.00	3.00
21	4.00	3.00	2.50	3.00	4.00	4.00	3.00	5.00	3.00
22	4.50	3.50	4.44	4.50	3.50	4.00	4.00	5.00	4.00
23	3.50	3.50	4.00	5.00	3.00	4.00	4.00	5.00	3.50
24	3.00	3.50	4.55	3.00	4.00	3.00	4.00	5.00	3.00
25	3.00	3.00	0.33	2.00	2.00	3.00	4.00	5.00	3.00
26	4.00	4.00	1.58	2.00	5.00	4.00	5.00	5.00	3.00
27	4.00	4.00	0.56	2.00	2.50	4.00	3.00	5.00	3.00
28	4.00	4.00	0.42	2.00	2.00	3.00	4.00	5.00	3.00
29	3.50	4.00	1.25	2.00	4.50	4.50	2.50	5.00	3.00
30	4.00	4.00	1.67	3.00	5.00	4.00	3.00	5.00	4.00

The values above are used to compute a single Thrust score as displayed in Figure A5. Equal weights are assigned to the criteria in the single score calculations.

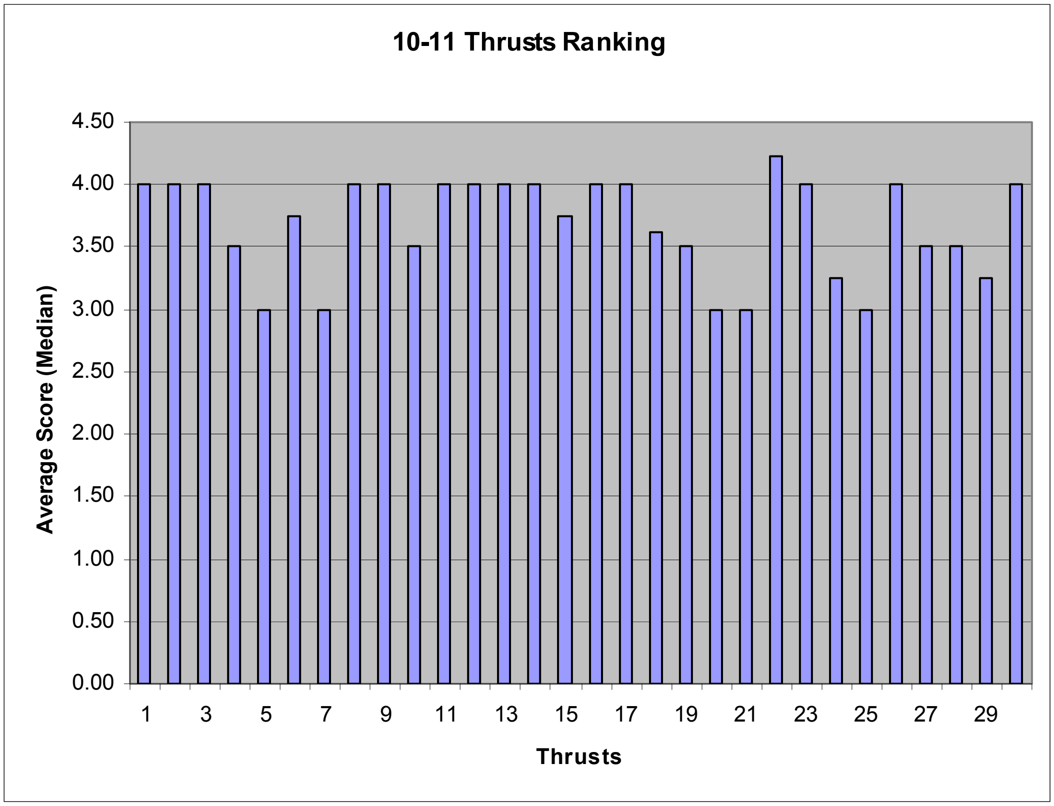


Figure A5. Thrust scores computed by median 2010-2011.

Table A6 below, contains the average score for each Thrust in fiscal year 2010-2011. The average values are calculated by mode of the project scores in each Thrust.

Table A6. Mode of project scores within each Thrust for fiscal year 2010-2011

Thrust	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverag e DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
1	4.00	4.00	1.67	3.00	3.00	5.00	3.00	5.00	4.00
2	5.00	4.00	2.33	4.00	3.00	4.00	3.00	5.00	4.00
3	4.00	3.00	1.00	4.00	5.00	4.00	5.00	5.00	3.00
4	4.00	3.00	0.83	2.00	5.00	4.00	5.00	5.00	2.00
5	3.00	3.00	0.00	2.00	1.00	4.00	5.00	5.00	3.00
6	3.00	4.00	2.22	5.00	5.00	3.00	5.00	5.00	3.00
7	2.00	3.00	2.08	3.00	5.00	3.00	5.00	5.00	2.00
8	3.00	5.00	2.50	2.00	1.00	4.00	5.00	5.00	4.00
9	5.00	3.00	0.00	5.00	1.00	3.00	5.00	5.00	3.00
10	3.00	4.00	0.63	3.00	3.00	5.00	5.00	5.00	3.00
11	4.00	4.00	1.25	3.00	4.00	4.00	4.00	5.00	3.00
12	4.00	3.00	1.92	5.00	1.00	5.00	5.00	5.00	4.00
13	4.00	4.00	1.32	3.00	5.00	4.00	4.00	4.00	3.00
14	4.00	4.00	2.08	2.00	3.00	4.00	5.00	5.00	4.00
15	4.00	4.00	2.00	3.00	4.00	4.00	4.00	5.00	4.00
16	4.00	4.00	2.27	4.00	3.00	4.00	4.00	5.00	3.00
17	4.00	4.00	2.50	4.00	4.00	4.00	4.00	5.00	3.00
18	2.00	3.00	3.75	3.00	3.00	5.00	5.00	5.00	3.00
19	3.00	3.00	5.00	3.00	4.00	4.00	5.00	5.00	2.00
20	4.00	3.00	2.78	3.00	3.00	3.00	4.00	4.00	3.00
21	4.00	3.00	2.50	3.00	4.00	4.00	3.00	5.00	3.00
22	5.00	3.00	4.44	4.00	4.00	4.00	4.00	5.00	5.00
23	3.50	4.00	4.00	5.00	2.00	4.00	4.00	5.00	3.00
24	2.00	4.00	4.55	3.00	4.00	4.00	4.00	5.00	3.00
25	3.00	4.00	0.33	2.00	1.00	4.00	4.00	5.00	3.00
26	4.00	4.00	1.58	2.00	5.00	4.00	5.00	5.00	3.00
27	4.00	4.00	0.56	2.00	2.00	4.00	3.00	5.00	3.00
28	4.00	4.00	0.42	2.00	2.00	3.00	4.00	5.00	3.00
29	4.00	4.00	1.25	2.00	5.00	5.00	2.00	5.00	4.00
30	4.00	4.00	1.67	3.00	5.00	4.00	4.00	5.00	4.00

The values above are used to compute a single Thrust score as displayed in Figure A6. Equal weights are assigned to the criteria in the single score calculations.

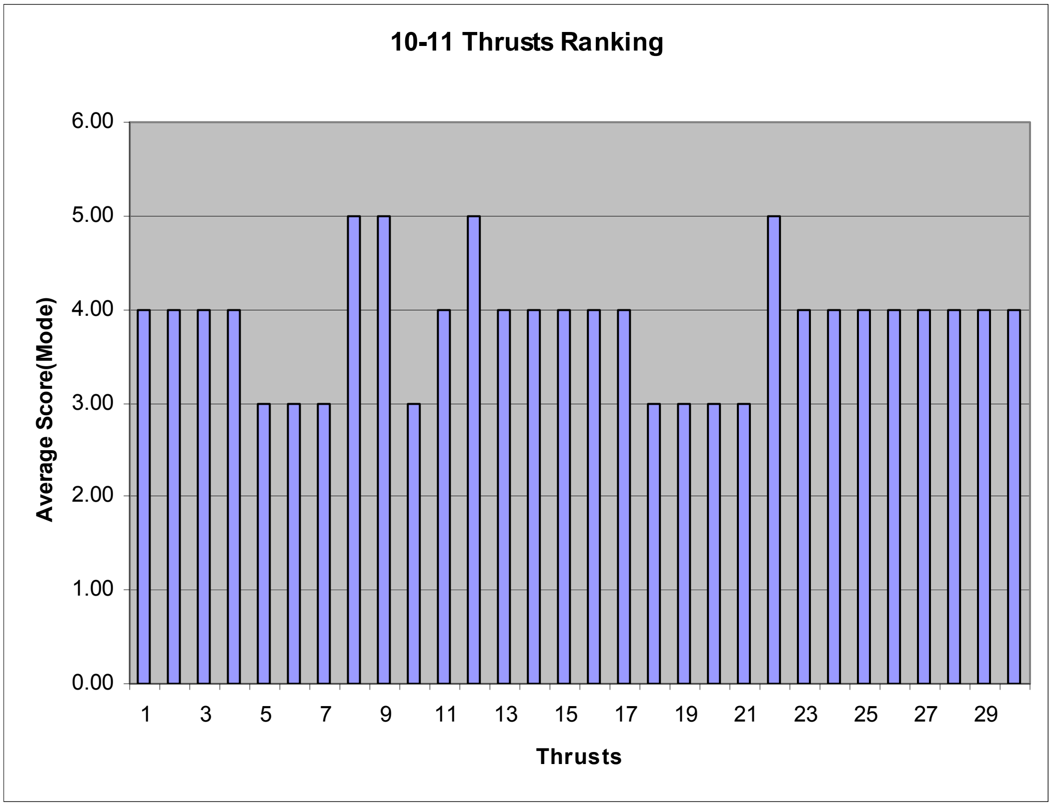


Figure A6. Thrust scores computed by mode 2010-2011.

Tables A7 and A8 provide insight into percentage of increase/decrease in DND leveraging, DRDC funds, FTE assignment and Thrust scores from fiscal year 2009-2010 to 2010-2011.

Table A7. 2 year comparison for DND Leveraging and DND funds for Thrusts

	DND Leveraging ($)			DRDC Funds ($)		
Thrust	**2009-2010**	**2010-2011**	**% Increase**	**2009-2010**	**2010-2011**	**% Increase**
1	10,000	10,000	0.00	375,000	800,000	113.33
2	362,000	148,000	-59.12	875,000	1,300,000	48.57
3	1,125,900	85,000	-92.45	1,543,000	1,850,000	19.90
4	6,122,000	1,574,000	-74.29	1,026,000	1,295,000	26.22
5	366,600	365,000	-0.44	1,215,000	1,095,000	-9.88
6	6,374,600	1,418,500	-77.75	1,578,000	1,860,000	17.87
7	3,597,090	150,500	-95.82	1,115,000	1,255,000	12.56
8	270,000	40,000	-85.19	880,000	1,275,000	44.89
9	0	0	0.00	320,000	325,000	1.56
10	205,500	205,500	0.00	623,000	900,000	44.46
11	749,000	11,344,900	1414.67	580,000	325,000	-43.97
12	2,101,350	4,391,500	108.98	811,000	910,000	12.21
13	5,573,200	7,744,000	38.95	2,005,000	2,481,700	23.78
14	2,074,985	3,294,460	58.77	1,025,000	1,036,000	1.07
15	925,000	755,000	-18.38	620,000	514,000	-17.10
16	1,004,700	742,100	-26.14	1,018,000	1,255,000	23.28
17	6,350,220	5,966,000	-6.05	725,000	1,060,000	46.21
18	80,000	370,000	362.50	305,000	995,000	226.23
19	1,280,400	76,700	-94.01	1,360,000	1,410,000	3.68
20	2,853,000	3,477,000	21.87	1,155,000	1,175,000	1.73
21	0	0	0.00	350,000	295,000	-15.71
22	455,000	450,000	-1.10	450,000	935,000	107.78
23	200,000	0	-100.00	332,000	270,000	-18.67
24	50,000	45,000	-10.00	1,013,000	980,000	-3.26
25	135,000	151,100	11.93	1,386,000	875,000	-36.87
26	167,000	602,000	260.48	2,107,000	1,759,000	-16.52
27	658,000	338,000	-48.63	929,500	1,415,000	52.23
28	150,000	30,000	-80.00	1,405,000	1,705,000	21.35
29	1,943,000	2,307,000	18.73	1,109,000	850,000	-23.35
30	1,510,000	1,960,000	29.80	1,439,000	1,634,000	13.55

Table A8. 2 year comparison for FTE quantities and overall ratings for Thrusts with equal weighting of the scores

	FTEs Quantity (Scientists)			Ratings (Mean)		
Thrust	2009-2010	2010-2011	% Increase	2009-2010	2010-2011	% Increase
1	22.75	19.13	-15.91	3.58	3.58	0.00
2	16.99	20.23	19.07	3.52	3.53	0.50
3	22.84	17.03	-25.44	3.48	3.42	-1.83
4	17.45	17.60	0.86	3.38	3.49	3.33
5	7.95	7.05	-11.32	3.02	3.14	4.14
6	24.25	28.10	15.88	3.50	3.57	2.16
7	25.26	22.81	-9.70	3.27	3.42	4.63
8	11.53	9.60	-16.74	3.56	3.63	1.84
9	10.07	10.12	0.50	3.50	3.50	0.00
10	15.20	11.30	-25.66	3.52	3.65	3.80
11	18.90	16.30	-13.76	3.59	3.55	-1.01
12	13.34	12.68	-4.95	3.69	3.49	-5.50
13	35.31	33.20	-5.98	3.57	3.59	0.58
14	15.31	13.00	-15.09	3.47	3.83	10.35
15	9.36	9.80	4.70	3.91	3.69	-5.60
16	6.80	7.45	9.56	3.58	3.58	0.00
17	18.30	13.32	-27.21	3.77	3.74	-0.75
18	5.95	6.10	2.52	3.65	3.41	-6.57
19	2.93	2.25	-23.21	3.73	3.73	0.00
20	7.70	5.20	-32.47	3.17	3.10	-2.38
21	16.52	9.60	-41.89	3.67	3.56	-2.84
22	21.88	24.92	13.89	4.34	4.27	-1.60
23	9.23	11.70	26.76	4.06	4.00	-1.54
24	15.52	15.35	-1.10	3.78	3.72	-1.51
25	9.05	13.47	48.84	2.99	2.91	-2.60
26	19.41	13.81	-28.85	3.60	3.53	-2.12
27	11.85	10.50	-11.39	3.26	3.16	-2.88
28	19.21	19.69	2.50	3.35	3.30	-1.52
29	26.70	25.10	-5.99	3.41	3.20	-6.16
30	27.08	24.81	-8.38	3.60	3.48	-3.23

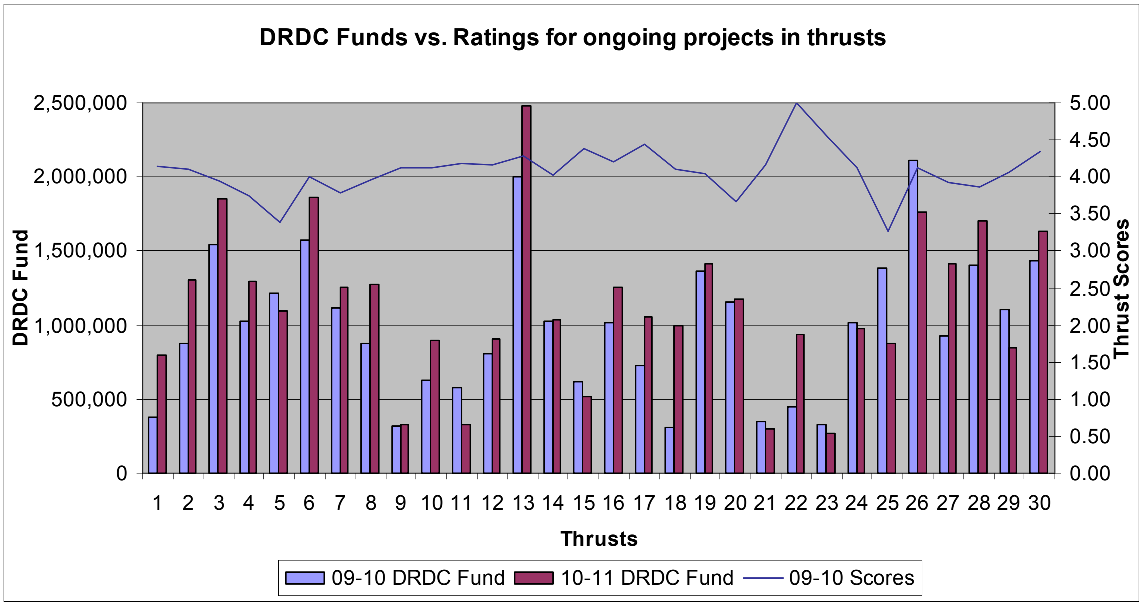


Figure A7. DRDC funds over 09-10 and 10-11 versus ratings in 09-10 for ongoing projects

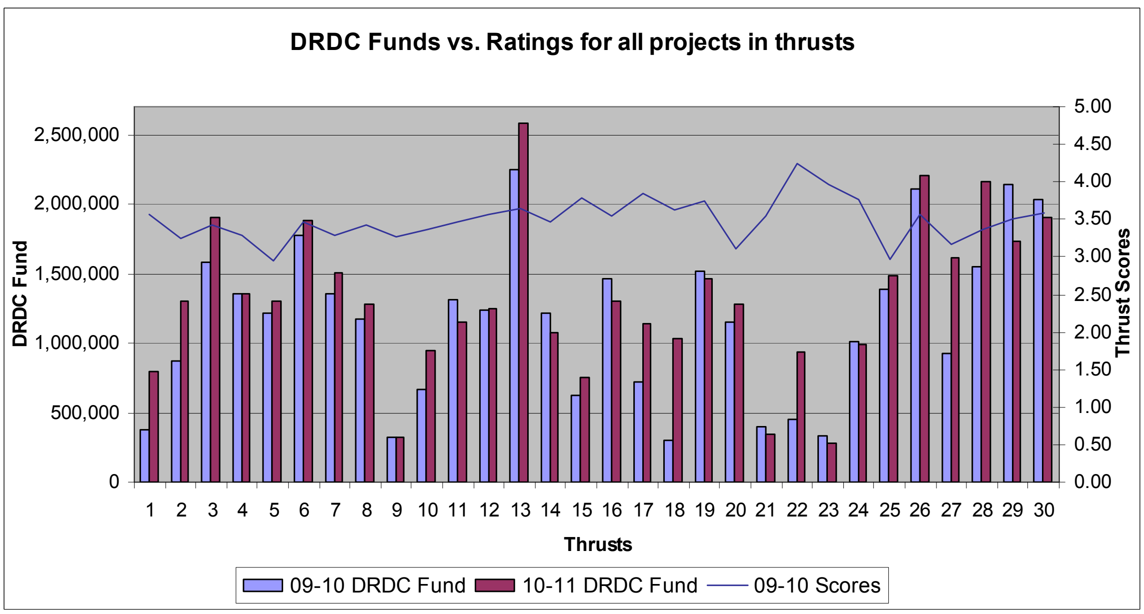


Figure A8. DRDC funds over 09-10 and 10-11 versus ratings in 09-10 for all projects

Table A9. contains the Thrusts and their project scores. The median is used to calculate the average of criterion ‘Scope’ and ‘Budget Management’. The rest of criteria are averaged using arithmetic mean.

Table A9. Project scores and computation of Thrust scores

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
1	5	4	No	3	3	5	5	5	5
2	4	4	Yes	5	5	4	4	5	4
3	4	4	No	4	3	4	4	5	5
4	5	3	No	3	4	5	3	5	3
5	5	5	Yes	3	4	4	3	5	4
6	4	3	No	3	3	3	3	5	3
7	4	4	Yes	4	3	5	3	5	4
8	4	3	No	3	3	1	1	5	2
9	5	4	No	2	3	3	1	0	3
Thrust1	**4.44**	**3.78**	**1.67**	**3.33**	**3.44**	**4.00**	**3.00**	**5.00**	**3.67**
10	5	3	Yes	4	4	4	4	5	4
11	3	3	Yes	5	4	4	4	5	4
12	4	4	No	1	3	5	2	5	3
13	4	5	No	2	3	5	3	5	4
14	3	3	Yes	3	1	5	3	5	3
15	4	5	Yes	5	3	4	4	4	5
16	5	4	No	4	4	4	4	5	5
17	4	4	No	4	3	4	4	4	4
18	3	4	No	3	4	3	3	4	3
19	5	5	No	3	1	5	3	3	4
20	5	4	Yes	5	1	2	1	3	3
21	5	4	No	4	2	1	3	4	4
22	4	3	Yes	4	3	2	3	2	4
23	3	4	No	3	3	5	3	3	3
24	3	4	Yes	3	3	3	2	4	3
Thrust2	**4.00**	**3.93**	**2.06**	**3.53**	**2.80**	**4.00**	**3.07**	**4.00**	**3.73**
25	4	3	No	2	4	4	2	3	3
26	5	4	yes	4	3	4	4	4	4
27	4	3	No	2	5	4	4	5	3
28	4	4	No	2	4	4	5	4	4

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
29	5	5	No	4	5	4	5	5	5
30	4	5	Yes	4	4	4	5	5	4
31	3	4	Yes	2	5	4	3	5	2
32	3	3	No	4	5	4	5	5	3
33	5	5	No	4	2	4	4	5	3
34	4	4	No	3	1	4	4	5	3
35	4	3	No	4	1	4	3	5	3
36	3	2	No	3	1	2	2	4	2
Thrust3	**4.00**	**3.75**	**1.43**	**3.17**	**3.33**	**4.00**	**3.83**	**5.00**	**3.25**
37	5	4	Yes	5	5	5	5	5	5
38	3	3	No	1	5	2	4	5	3
39	4	3	No	3	2	2	3	5	2
40	4	3	No	2	1	3	4	5	3
41	3	3	No	3	1	5	5	5	3
42	4	3	No	5	5	4	4	5	3
43	4	4	Yes	4	5	2	3	5	2
44	4	3	No	2	4	5	5	5	3
45	5	4	No	4	4	3	4	5	3
46	3	4	No	2	1	5	5	5	3
Thrust4	**3.90**	**3.40**	**0.83**	**3.10**	**3.30**	**3.50**	**4.20**	**5.00**	**3.00**
47	3	3	No	4	2	5	4	5	3
48	3	4	No	2	1	3	4	5	3
49	4	4	No	2	4	4	2	5	4
50	3	4	No	2	1	3	2	5	2
51	2	3	No	2	4	2	3	4	2
52	4	3	No	5	2	3	4	5	3
53	4	3	No	4	1	4	4	5	3
Thrust5	**3.29**	**3.43**	**0.00**	**3.00**	**2.14**	**3.00**	**3.29**	**5.00**	**2.86**
54	4	3	No	3	5	3	3	5	3
55	2	5	No	1	4	2	2	5	3
56	3	4	No	3	2	3	3	5	3

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
57	5	4	Yes	4	3	3	4	5	3
58	3	4	No	4	5	3	3	5	3
59	3	5	No	3	5	4	4	5	4
60	5	3	Yes	5	5	2	3	5	3
61	2	3	Yes	5	4	4	3	3	3
62	5	3	Yes	4	4	4	4	5	3
63	3	3	No	3	1	4	2	5	3
64	5	3	No	5	4	3	3	3	3
65	3	2	Yes	3	1	3	3	3	3
66	3	4	Yes	5	2	4	5	5	3
67	4	4	Yes	5	4	5	5	5	4
68	5	4	Yes	5	5	4	3	5	5
69	3	4	No	5	5	3	1	5	3
Thrust6	**3.63**	**3.63**	**2.37**	**3.94**	**3.69**	**3.00**	**3.19**	**5.00**	**3.25**
70	4	3	Yes	5	5	2	1	5	2
71	1	2	Yes	5	2	4	3	5	3
72	4	4	Yes	4	1	5	4	5	3
73	3	4	No	3	3	4	3	5	3
74	2	4	No	3	4	5	5	5	4
75	4	3	Yes	4	1	4	2	5	3
76	3	3	No	5	3	3	2	5	2
77	2	3	No	3	3	3	3	5	3
78	2	3	No	3	5	4	5	4	3
79	1	3	Yes	3	5	3	2	4	2
Thrust7	**2.60**	**3.20**	**2.27**	**3.80**	**3.20**	**4.00**	**3.00**	**5.00**	**2.80**
80	3	5	Yes	2	1	2	4	5	3
81	3	5	No	3	2	5	4	5	3
82	4	4	No	3	4	5	5	5	4
83	3	4	No	2	1	4	5	5	3
84	4	3	Yes	4	3	3	4	5	3
85	3	2	Yes	2	1	4	5	5	3

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
Thrust8	**3.33**	**3.83**	**2.14**	**2.67**	**2.00**	**4.00**	**4.50**	**5.00**	**3.17**
86	5	3	No	5	2	3	3	5	3
87	5	3	No	5	1	3	3	5	3
88	4	3	No	4	1	5	5	5	4
Thrust9	**4.67**	**3.00**	**0.00**	**4.67**	**1.33**	**3.00**	**3.67**	**5.00**	**3.33**
89	4	5	No	3	3	5	5	5	3
90	3	4	No	4	4	5	5	5	3
91	3	5	No	2	3	5	5	5	3
92	3	4	No	3	2	5	5	5	2
93	4	4	No	3	3	5	5	5	3
94	4	3	Yes	4	3	5	4	5	3
95	3	4	No	4	1	3	3	3	2
Thrust10	**3.43**	**4.14**	**0.56**	**3.29**	**2.71**	**5.00**	**4.57**	**5.00**	**2.71**
96	4	4	No	3	4	4	4	5	3
97	4	4	Yes	3	4	4	4	5	3
98	4	4	No	3	4	4	4	5	3
99	4	4	Yes	5	4	5	5	5	3
100	4	4	No	4	3	4	4	5	2
101	4	4	Yes	4	3	4	4	5	2
102	3	4	No	2	3	4	4	5	2
Thrust11	**3.86**	**4.00**	**1.54**	**3.43**	**3.57**	**4.00**	**4.14**	**5.00**	**2.57**
103	4	3	Yes	4	2	5	2	4	4
104	4	3	No	5	3	3	3	0	1
105	5	5	No	3	4	4	5	5	5
106	2	4	No	2	3	2	3	0	1
107	3	3	Yes	5	2	4	5	5	2
108	5	5	Yes	5	1	3	5	5	4
109	4	2	Yes	4	1	5	4	5	2
110	4	3	Yes	5	1	5	5	5	3
111	3	4	No	2	1	5	5	5	2
Thrust12	**3.78**	**3.56**	**2.69**	**3.89**	**2.00**	**4.00**	**4.11**	**5.00**	**2.67**

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
112	4	5	No	2	5	4	4	4	3
113	4	4	No	3	5	4	4	4	2
114	4	5	No	2	4	4	4	5	3
115	4	4	No	5	4	4	5	5	4
116	3	4	No	3	4	4	4	4	2
117	4	4	No	3	4	4	4	4	3
118	4	3	No	3	5	4	3	4	3
119	5	5	Yes	4	5	4	5	5	4
120	4	3	Yes	3	4	4	4	4	3
121	5	4	No	5	5	4	3	4	5
122	4	3	No	5	5	4	5	5	4
123	4	4	Yes	4	4	3	4	4	4
124	4	4	No	2	5	4	5	5	3
125	4	4	No	3	4	4	5	5	3
126	4	4	No	3	5	4	5	5	3
127	4	3	Yes	4	4	4	4	4	4
128	5	3	Yes	5	4	4	4	4	4
129	4	4	No	2	2	4	4	4	2
Thrust13	**4.11**	**3.89**	**1.32**	**3.39**	**4.33**	**4.00**	**4.22**	**4.00**	**3.28**
130	4	4	Yes	4	4	3	5	5	3
131	4	4	No	3	3	3	3	5	2
132	3	4	No	2	2	4	4	5	2
133	4	4	Yes	2	4	4	4	5	3
134	4	4	Yes	5	4	4	4	5	3
135	4	4	No	2	3		3	5	2
136	4	4	No	4	3		3	5	4
137	4	4	Yes	4	3	4	2	5	2
138	3	3	No	2	2	4	4	4	2
Thrust14	**3.78**	**3.89**	**2.27**	**3.11**	**3.11**	**4.00**	**3.56**	**5.00**	**2.56**
139	4	4	Yes	3	2	4	4	5	4
140	3	3	No	3	4	4	4	5	3

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
141	4	4	Yes	5	4	4	5	5	4
142	4	3	Yes	4	1	3	4	5	3
Thrust15	**3.75**	**3.50**	**3.75**	**3.75**	**2.75**	**4.00**	**4.25**	**5.00**	**3.50**
143	5	4	No	3	3	4	3	5	3
144	4	4	No	3	3	4	4	5	3
145	4	4	Yes	4	5	4	4	5	4
146	4	4	Yes	4	3	4	4	3	3
147	4	4	No	2	2	2	3	5	2
148	4	5	No	3	3	3	3	5	2
149	4	3	Yes	4	5	3	4	5	3
150	3	3	Yes	4	3	3	3	5	3
151	4	5	Yes	4	4	5	5	5	3
152	4	4	No	3	3	4	4	5	3
Thrust16	**4.00**	**4.00**	**2.27**	**3.40**	**3.40**	**4.00**	**3.70**	**5.00**	**2.90**
153	5	4	Yes	4	5	2	3	5	4
154	4	4	Yes	5	5	4	4	5	4
155	5	4	No	4	5	5	5	5	3
156	3	3	No	3	4	4	4	5	3
157	4	3	Yes	5	5	2	2	5	4
158	3	4	Yes	3	4	4	5	5	5
159	4	4	No	2	4	5	4	4	3
160	4	4	Yes	4	4	4	4	5	3
161	4	4	No	4	5	4	4	5	3
162	3	3	No	4	4		3	4	3
163	4	4	Yes	3	4	4	5	5	4
Thrust17	**3.91**	**3.73**	**2.73**	**3.73**	**4.45**	**4.00**	**3.91**	**5.00**	**3.55**
164	4	4	Yes	3	3	5	5	5	3
165	2	4	Yes	3	3	4	5	5	3
166	4	3	Yes	4	4	2	2	2	2
167	4	3	Yes	3	3	5	5	5	2
168	2	4	Yes	1	3	5	5	4	2

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
169	2	4	Yes	2	5	5	1	4	3
Thrust18	**3.00**	**3.67**	**5.00**	**2.67**	**3.50**	**5.00**	**3.83**	**4.50**	**2.50**
170	3	3	Yes	3	4	4	5	5	3
171	3	3	Yes	1	4	4	3	5	2
172	3	3	Yes	3	4	4	3	5	2
173	3	3	Yes	3	4	5	5	5	3
174	3	4	Yes	2	4	3	4	5	2
175	3	4	Yes	2	4	4	5	5	2
176	4	3	Yes	4	4	5	5	5	3
177	3	4	Yes	2	4	4	5	5	2
Thrust19	**3.13**	**3.38**	**5.00**	**2.50**	**4.00**	**4.00**	**4.38**	**5.00**	**2.38**
178	3	3	No	3	3	4	4	4	3
179	4	4	Yes	3	3	3	4	4	4
180	4	4	Yes	4	3		4	5	3
181	3	3	No	2	3	3	2	4	3
182	2	4	Yes	1	3	3	3	4	3
183	4	3	No	1	4	4	4	4	3
184	4	4	Yes	4	4	3	4	5	3
185	2	3	No	1	2	3	3	4	2
Thrust20	**3.25**	**3.50**	**2.22**	**2.38**	**3.13**	**3.00**	**3.50**	**4.00**	**3.00**
186	4	3	Yes	5	3	4	3	5	2
187	4	3	No	3	4	4	3	5	3
188	3	3	Yes	3	3	4	5	5	3
189	4	3	Yes	3	4	4	3	5	3
190	5	3	Yes	4	4	4	4	5	3
Thrust21	**4.00**	**3.00**	**3.33**	**3.60**	**3.60**	**4.00**	**3.60**	**5.00**	**2.80**
191	5	5	Yes	4	4	4	4	4	3
192	5	3	Yes	5	4	4	4	5	5
193	4	3	Yes	4	2	4	4	5	4
194	4	4	Yes	4	2	3	4	5	4
195	5	3	Yes	5	3	4	4	5	5

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
196	5	3	Yes	5	3	4	4	5	5
197	4	5	Yes	5	5	4	5	5	4
198	4	5	Yes	4	4	4	3	5	3
Thrust22	**4.50**	**3.88**	**5.00**	**4.50**	**3.38**	**4.00**	**4.00**	**5.00**	**4.13**
199	4	3	Yes	5	2	4	4	5	3
200	5	4	Yes	5	5	4	4	5	5
201	3	4	Yes	4	4	3	4	5	4
202	2	2	Yes	3	2	4	4	5	3
Thrust23	**3.50**	**3.25**	**5.00**	**4.25**	**3.25**	**4.00**	**4.00**	**5.00**	**3.75**
203	2	4	Yes	3	4		4	5	3
204	4	4	Yes	4	3	3	3	5	3
205	3	3	Yes	3	4	4	4	5	2
206	2	4	Yes	3	4	4	4	5	3
207	4	4	Yes	2	3	5	5	5	3
208	3	3	Yes	5	5	1	5	5	4
209	3	3	Yes	5	5	1	3	5	3
210	2	3	Yes	3	2	3	5	5	2
211	1	3	Yes	3	5	4	5	5	2
212	5	4	Yes	5	2	2	4	5	5
Thrust24	**2.90**	**3.50**	**5.00**	**3.60**	**3.70**	**3.00**	**4.20**	**5.00**	**3.00**
213	3	4	No	3	4	4	5	5	3
214	2	3	No	1	2	3	4	5	1
215	2	2	No	1	1	4	5	5	3
216	4	3	No	2	3	3	4	5	4
217	4	3	No	2	2	2	4	5	3
218	3	4	No	2	5	1	5	5	4
219	3	1	No	3	1	0	4	0	3
220	3	3	No	2	1	0	4	5	3
221	2	4	No	3	1	0	4	5	3
222	4	4	No	2	3	0	5	5	3
Thrust25	**3.00**	**3.10**	**0.45**	**2.10**	**2.30**	**3.00**	**4.40**	**5.00**	**3.00**

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
223	4	4	YES	2	5	4	4	5	3
224	4	4	YES	2	5	4	5	3	3
225	3	5	YES	2	5	5	5	5	3
226	4	4	NO	2	3	4	5	4	3
227	3	4	YES	2	5	4	4	5	3
228	4	4	NO	2	5	4	5	5	4
229	4	4	NO	3	5	4	5	4	3
230	3	2	NO	2	2	4	3	5	3
231	4	2	NO	2	1	4	5	5	4
232	5	5	YES	5	5	5	5	5	4
233	4	3	NO	2	3	4	5	5	3
234	4	1	NO	1	1	1	5	5	3
235	5	5	YES	5	5	5	5	5	3
236	3	4	YES	2	4	5	3	5	3
Thrust26	**3.86**	**3.64**	**2.33**	**2.43**	**3.86**	**4.00**	**4.57**	**5.00**	**3.21**
237	5	4	No	3	2	4	4	4	4
238	3	4	No	2	2	4	3	4	3
239	4	4	No	3	3	4	3	5	3
240	4	4	No	2	3	4	4	5	4
241	4	4	No	3	5	3	3	5	4
242	3	4	No	2	2	3	3	5	3
243	5	4	Yes	5	3	4	3	5	3
244	4	3	No	2	1	3	3	4	3
Thrust27	**4.00**	**3.88**	**0.56**	**2.75**	**2.63**	**4.00**	**3.25**	**5.00**	**3.38**
245	4	4	No	2	4	2	4	5	2
246	5	4	No	2	2	2	4	5	3
247	4	3	No	3	1	2	2	5	2
248	5	4	Yes	5	2	3	4	5	4
249	4	5	No	2	4	3	5	5	4
250	5	4	No	2	2	2	5	5	4
251	4	5	No	1	3	4	4	5	3

Projects	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
Thrust28	**4.43**	**4.14**	**1.11**	**2.43**	**2.57**	**2.00**	**4.00**	**5.00**	**3.14**
252	4	4	yes	2	5	5	2	5	4
253	3	4	yes	3	5	5	2	5	3
254	3	4	no	2	2	5	3	4	3
255	4	4	yes	5	4	4	4	5	4
256	3	3	No	2	4	5	2	5	2
257	4	4	No	2	5	3	4	5	3
258	3	3	no	2	3	5	3	5	4
259	4	4	no	2	5	4	3	5	1
Thrust29	**3.50**	**3.75**	**2.31**	**2.50**	**4.13**	**5.00**	**2.88**	**5.00**	**3.00**
260	5	5	Yes	5	4	5	2	4	4
261	5	4	Yes	5	5	4	4	5	4
262	5	2	Yes	3	2	2	1	5	1
263	4	4	No	3	2	4	4	4	3
264	4	4	Yes	3	5	4	4	5	4
265	3	4	No	3	3	4	4	5	3
266	3	3	No	4	5	4	4	5	4
267	2	4	No	2	5	3	2	2	2
268	4	5	No	3	4	5	4	5	4
269	3	5	Yes	5	5	4	5	4	5
270	4	4	No	3	5	4	4	5	4
Thrust30	**3.82**	**4.00**	**2.14**	**3.55**	**4.09**	**4.00**	**3.45**	**5.00**	**3.45**

Appendix B – Projects' Scores Distribution Analysis

In this appendix, data analysis is performed on project scores to determine distribution. The data was extracted by '*R*' from text file "DRDC.txt" which was saved from Excel.

```
DRDC.data.eval=function(){
scores=matrix(scan("DRDC.txt"),ncol=8,byrow=T)
temp <- rep(0, 270)
par(mfrow=c(2,1))

hist(scores[,1],main=paste("Density Function,
Leverage"),xlab="Project Scores",xlim=c(0,5),breaks=5)

hist(scores[,2],main=paste("Density Function, Hard
Problems"),xlab="Project Scores",xlim=c(0,5),breaks=5)

hist(scores[,3],main=paste("Density Function,
Originality"),xlab="Project Scores",xlim=c(0,5),breaks=5)

hist(scores[,4],main=paste("Density Function, Potential for
uptake"),xlab="Project Scores",xlim=c(0,5),breaks=5)

hist(scores[,5],main=paste("Density Function,
Scope"),xlab="Project Scores",xlim=c(0,5),breaks=5)

hist(scores[,6],main=paste("Density Function, Schedule
Mgt"),xlab="Project Scores",xlim=c(0,5),breaks=5)

hist(scores[,7],main=paste("Density Function, Budget
Mgt"),xlab="Project Scores",xlim=c(0,5),breaks=5)

hist(scores[,8],main=paste("Density Function,
Quality"),xlab="Project Scores",xlim=c(0,5),breaks=5)
}
```

Following is the content of the file “DRDC.txt” that was used in the above program. It contains the score of projects with respect to the following criteria: Leverage, Hard Problems, Originality, Potential for uptake, Scope, Schedule Management, Budget Management and Quality.

```
5	4	3	3	5	5	5	5
4	4	5	5	4	4	5	4
4	4	4	3	4	4	5	5
5	3	3	4	5	3	5	3
5	5	3	4	4	3	5	4
4	3	3	3	3	3	5	3
4	4	4	3	5	3	5	4
4	3	3	3	1	1	5	2
5	4	2	3	3	1	4	3
5	3	4	4	4	4	5	4
3	3	5	4	4	4	5	4
4	4	1	3	5	2	5	3
4	5	2	3	5	3	5	4
3	3	3	1	5	3	5	3
4	5	5	3	4	4	4	5
5	4	4	4	4	4	5	5
4	4	4	3	4	4	4	4
3	4	3	4	3	3	4	3
5	5	3	1	5	3	3	4
5	4	5	1	2	1	3	3
5	4	4	2	1	3	4	4
4	3	4	3	2	3	2	4
3	4	3	3	5	3	3	3
3	4	3	3	3	2	4	3
4	3	2	4	4	2	3	3
5	4	4	3	4	4	4	4
4	3	2	5	4	4	5	3
4	4	2	4	4	5	4	4
5	5	4	5	4	5	5	5
4	5	4	4	4	5	5	4
3	4	2	5	4	3	5	2
3	3	4	5	4	5	5	3
5	5	4	2	4	4	5	3
4	4	3	1	4	4	5	3
4	3	4	1	4	3	5	3
3	2	3	1	2	2	4	2
5	4	5	5	5	5	5	5
3	3	1	5	2	4	5	3
4	3	3	2	2	3	5	2
4	3	2	1	3	4	5	3
3	3	3	1	5	5	5	3
4	3	5	5	4	4	5	3
4	4	4	5	2	3	5	2
4	3	2	4	5	5	5	3
5	4	4	4	3	4	5	3
3	4	2	1	5	5	5	3
```

3	3	4	2	5	4	5	3
3	4	2	1	3	4	5	3
4	4	2	4	4	2	5	4
3	4	2	1	3	2	5	2
2	3	2	4	2	3	4	2
4	3	5	2	3	4	5	3
4	3	4	1	4	4	5	3
4	3	3	5	3	3	5	3
2	5	1	4	2	2	5	3
3	4	3	2	3	3	5	3
5	4	4	3	3	4	5	3
3	4	4	5	3	3	5	3
3	5	3	5	4	4	5	4
5	3	5	5	2	3	5	3
2	3	5	4	4	3	3	3
5	3	4	4	4	4	5	3
3	3	3	1	4	2	5	3
5	3	5	4	3	3	3	3
3	2	3	1	3	3	3	3
3	4	5	2	4	5	5	3
4	4	5	4	5	5	5	4
5	4	5	5	4	3	5	5
3	4	5	5	3	1	5	3
4	3	5	5	2	1	5	2
1	2	5	2	4	3	5	3
4	4	4	1	5	4	5	3
3	4	3	3	4	3	5	3
2	4	3	4	5	5	5	4
4	3	4	1	4	2	5	3
3	3	5	3	3	2	5	2
2	3	3	3	3	3	5	3
2	3	3	5	4	5	4	3
1	3	3	5	3	2	4	2
3	5	2	1	2	4	5	3
3	5	3	2	5	4	5	3
4	4	3	4	5	5	5	4
3	4	2	1	4	5	5	3
4	3	4	3	3	4	5	3
3	2	2	1	4	5	5	3
5	3	5	2	3	3	5	3
5	3	5	1	3	3	5	3
4	3	4	1	5	5	5	4
4	5	3	3	5	5	5	3
3	4	4	4	5	5	5	3
3	5	2	3	5	5	5	3
3	4	3	2	5	5	5	2
4	4	3	3	5	5	5	3
4	3	4	3	5	4	5	3
3	4	4	1	3	3	3	2
4	4	3	4	4	4	5	3
4	4	3	4	4	4	5	3
4	4	3	4	4	4	5	3

4	4	5	4	5	5	5	3
4	4	4	3	4	4	5	2
4	4	4	3	4	4	5	2
3	4	2	3	4	4	5	2
4	3	4	2	5	2	4	4
4	3	5	3	3	3	4	1
5	5	3	4	4	5	5	5
2	4	2	3	2	3	4	1
3	3	5	2	4	5	5	2
5	5	5	1	3	5	5	4
4	2	4	1	5	4	5	2
4	3	5	1	5	5	5	3
3	4	2	1	5	5	5	2
4	5	2	5	4	4	4	3
4	4	3	5	4	4	4	2
4	5	2	4	4	4	5	3
4	4	5	4	4	5	5	4
3	4	3	4	4	4	4	2
4	4	3	4	4	4	4	3
4	3	3	5	4	3	4	3
5	5	4	5	4	5	5	4
4	3	3	4	4	4	4	3
5	4	5	5	4	3	4	5
4	3	5	5	4	5	5	4
4	4	4	4	3	4	4	4
4	4	2	5	4	5	5	3
4	4	3	4	4	5	5	3
4	4	3	5	4	5	5	3
4	3	4	4	4	4	4	4
5	3	5	4	4	4	4	4
4	4	2	2	4	4	4	2
4	4	4	4	3	5	5	3
4	4	3	3	3	3	5	2
3	4	2	2	4	4	5	2
4	4	2	4	4	4	5	3
4	4	5	4	4	4	5	3
4	4	2	3	0	3	5	2
4	4	4	3	0	3	5	4
4	4	4	3	4	2	5	2
3	3	2	2	4	4	4	2
4	4	3	2	4	4	5	4
3	3	3	4	4	4	5	3
4	4	5	4	4	5	5	4
4	3	4	1	3	4	5	3
5	4	3	3	4	3	5	3
4	4	3	3	4	4	5	3
4	4	4	5	4	4	5	4
4	4	4	3	4	4	3	3
4	4	2	2	2	3	5	2
4	5	3	3	3	3	5	2
4	3	4	5	3	4	5	3
3	3	4	3	3	3	5	3

4	5	4	4	5	5	5	3
4	4	3	3	4	4	5	3
5	4	4	5	2	3	5	4
4	4	5	5	4	4	5	4
5	4	4	5	5	5	5	3
3	3	3	4	4	4	5	3
4	3	5	5	2	2	5	4
3	4	3	4	4	5	5	5
4	4	2	4	5	4	4	3
4	4	4	4	4	4	5	3
4	4	4	5	4	4	5	3
3	3	4	4	0	3	4	3
4	4	3	4	4	5	5	4
4	4	3	3	5	5	5	3
2	4	3	3	4	5	5	3
4	3	4	4	2	2	2	2
4	3	3	3	5	5	5	2
2	4	1	3	5	5	4	2
2	4	2	5	5	1	4	3
3	3	3	4	4	5	5	3
3	3	1	4	4	3	5	2
3	3	3	4	4	3	5	2
3	3	3	4	5	5	5	3
3	4	2	4	3	4	5	2
3	4	2	4	4	5	5	2
4	3	4	4	5	5	5	3
3	4	2	4	4	5	5	2
3	3	3	3	4	4	4	3
4	4	3	3	3	4	4	4
4	4	4	3	0	4	5	3
3	3	2	3	3	2	4	3
2	4	1	3	3	3	4	3
4	3	1	4	4	4	4	3
4	4	4	4	3	4	5	3
2	3	1	2	3	3	4	2
4	3	5	3	4	3	5	2
4	3	3	4	4	3	5	3
3	3	3	3	4	5	5	3
4	3	3	4	4	3	5	3
5	3	4	4	4	4	5	3
5	5	4	4	4	4	4	3
5	3	5	4	4	4	5	5
4	3	4	2	4	4	5	4
4	4	4	2	3	4	5	4
5	3	5	3	4	4	5	5
5	3	5	3	4	4	5	5
4	5	5	5	4	5	5	4
4	5	4	4	4	3	5	3
4	3	5	2	4	4	5	3
5	4	5	5	4	4	5	5
3	4	4	4	3	4	5	4
2	2	3	2	4	4	5	3

2	4	3	4	0	4	5	3
4	4	4	3	3	3	5	3
3	3	3	4	4	4	5	2
2	4	3	4	4	4	5	3
4	4	2	3	5	5	5	3
3	3	5	5	1	5	5	4
3	3	5	5	1	3	5	3
2	3	3	2	3	5	5	2
1	3	3	5	4	5	5	2
5	4	5	2	2	4	5	5
3	4	3	4	4	5	5	3
2	3	1	2	3	4	5	1
2	2	1	1	4	5	5	3
4	3	2	3	3	4	5	4
4	3	2	2	2	4	5	3
3	4	2	5	1	5	5	4
3	1	3	1	0	4	4	3
3	3	2	1	0	4	5	3
2	4	3	1	0	4	5	3
4	4	2	3	0	5	5	3
4	4	2	5	4	4	5	3
4	4	2	5	4	5	3	3
3	5	2	5	5	5	5	3
4	4	2	3	4	5	4	3
3	4	2	5	4	4	5	3
4	4	2	5	4	5	5	4
4	4	3	5	4	5	4	3
3	2	2	2	4	3	5	3
4	2	2	1	4	5	5	4
5	5	5	5	5	5	5	4
4	3	2	3	4	5	5	3
4	1	1	1	1	5	5	3
5	5	5	5	5	5	5	3
3	4	2	4	5	3	5	3
5	4	3	2	4	4	4	4
3	4	2	2	4	3	4	3
4	4	3	3	4	3	5	3
4	4	2	3	4	4	5	4
4	4	3	5	3	3	5	4
3	4	2	2	3	3	5	3
5	4	5	3	4	3	5	3
4	3	2	1	3	3	4	3
4	4	2	4	2	4	5	2
5	4	2	2	2	4	5	3
4	3	3	1	2	2	5	2
5	4	5	2	3	4	5	4
4	5	2	4	3	5	5	4
5	4	2	2	2	5	5	4
4	5	1	3	4	4	5	3
4	4	2	5	5	2	5	4
3	4	3	5	5	2	5	3
3	4	2	2	5	3	4	3

4	4	5	4	4	4	5	4
3	3	2	4	5	2	5	2
4	4	2	5	3	4	5	3
3	3	2	3	5	3	5	4
4	4	2	5	4	3	5	1
5	5	5	4	5	2	4	4
5	4	5	5	4	4	5	4
5	2	3	2	2	1	5	1
4	4	3	2	4	4	4	3
4	4	3	5	4	4	5	4
3	4	3	3	4	4	5	3
3	3	4	5	4	4	5	4
2	4	2	5	3	2	2	2
4	5	3	4	5	4	5	4
3	5	5	5	4	5	4	5
4	4	3	5	4	4	5	4

Following figures are the outcome of the above program:

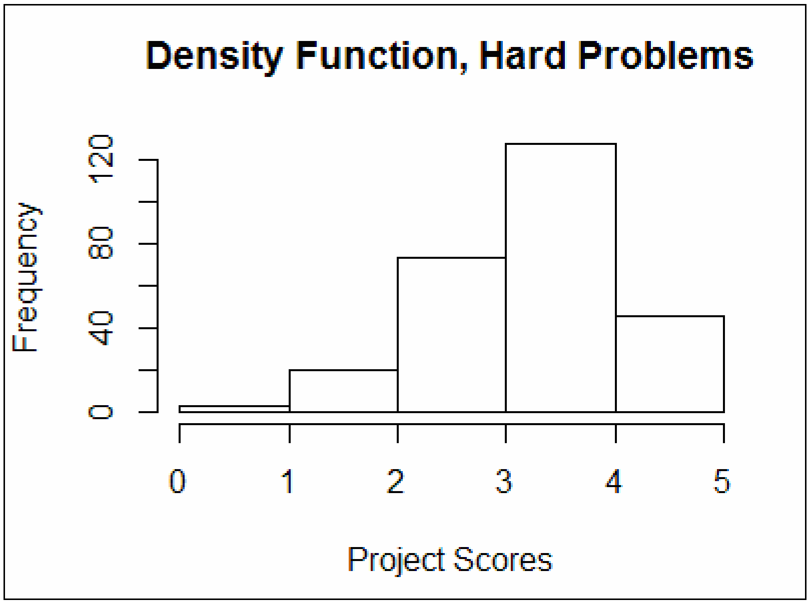


Figure B1. Histogram of project scores for Hard Problems

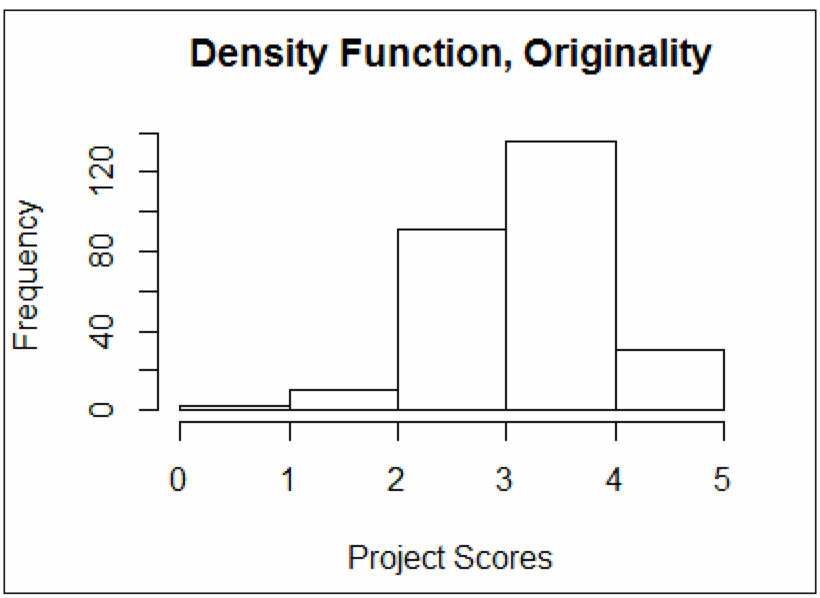


Figure B2. Histogram of project scores for Originality

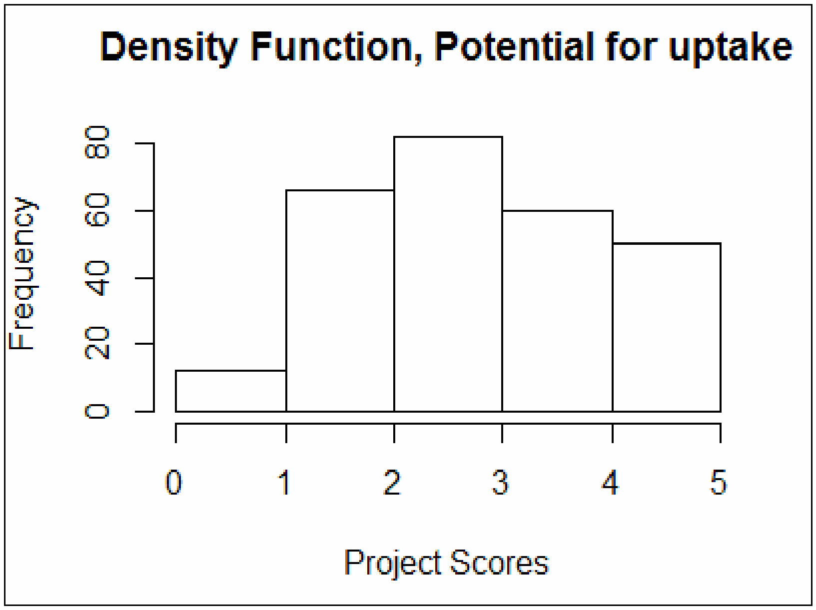


Figure B3. Histogram of project scores for Potential for Uptake

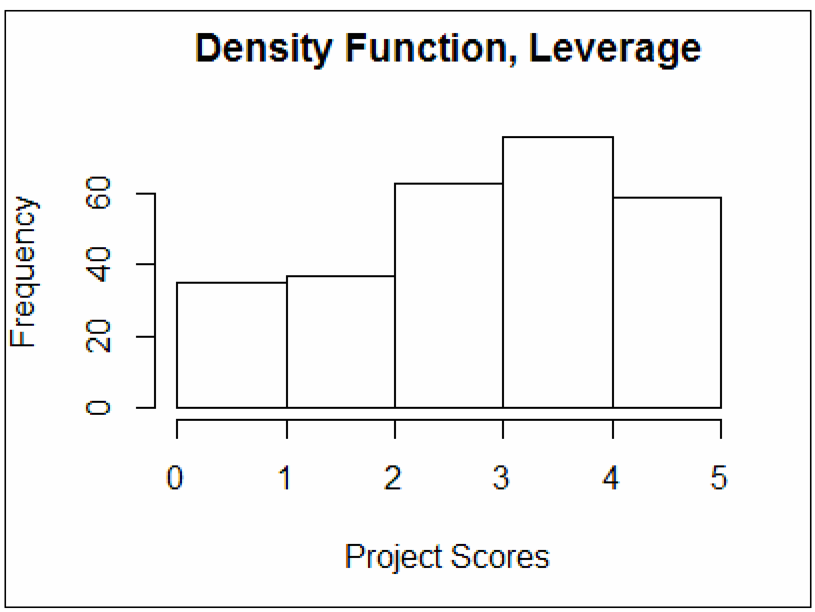


Figure B4. Histogram of project scores for Leverage

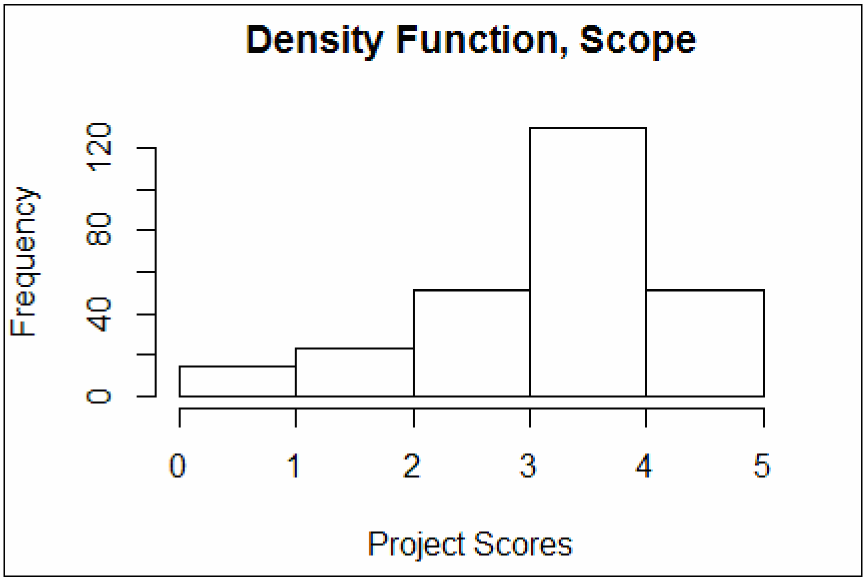


Figure B5. Histogram of project scores for Scope

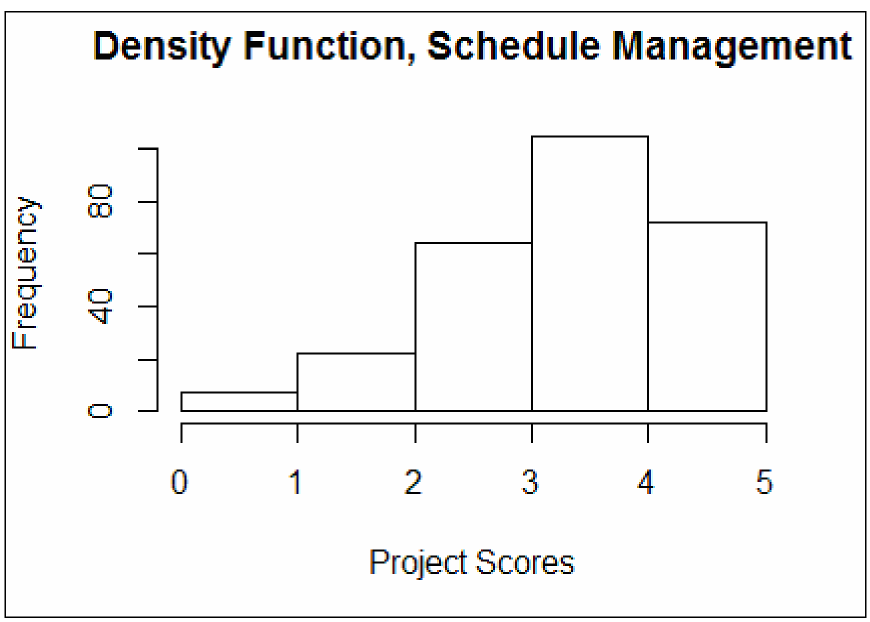


Figure B6. Histogram of project scores for Schedule Management

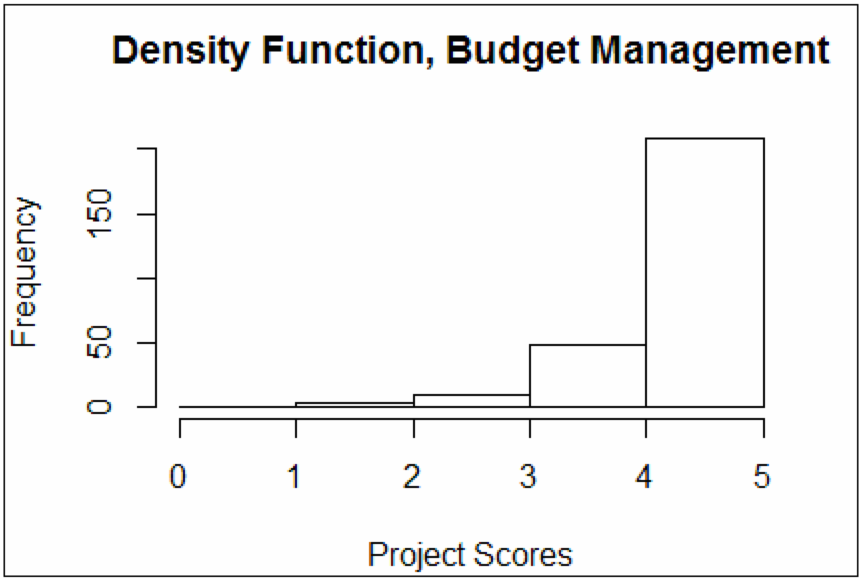


Figure B7. Histogram of project scores for Budget Management

Figure B8. Histogram of project scores for Quality

Appendix C – LP Data Elements

The variables in LP problem formulation consist of matrices described in this appendix. The values are derived from project data belonging to two successive fiscal years.

Following table is C_{ij} which represents the "benefit function" of having people of type *j* acting in Thrust *i*. Each entry contains a number between 0 and 100 signifying the importance of each type in a Thrust.

Table C1. The benefit function C_{ij}

Thrusts	Type1	Type2	Type3	Type4	Type5	Type6	Type7	Type8	Type9	Type10	Type11
1	0.00	0.00	0.00	15.52	0.00	0.00	0.00	0.00	0.00	0.00	38.33
2	1.83	0.00	0.00	34.34	0.00	0.00	0.00	0.00	0.00	0.00	2.37
3	0.00	0.00	9.23	0.00	0.00	0.00	0.00	77.50	5.74	0.45	0.00
4	1.47	0.32	11.04	2.94	0.42	0.00	9.57	0.00	23.35	0.42	0.00
5	14.78	0.00	0.18	8.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	2.74	0.46	54.06	7.64	10.15	3.54	0.00	25.22	7.76	2.05	0.00
7	0.92	0.00	1.64	11.17	0.51	59.01	0.96	0.00	19.26	0.00	0.00
8	18.90	0.00	11.85	1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.44	1.32	12.17	0.00	0.00	4.83	0.00	0.00	0.00	2.20
10	7.51	19.84	0.00	3.32	0.00	0.00	0.00	1.07	0.00	2.90	3.11
11	8.88	30.24	19.90	0.22	3.26	0.00	1.69	0.00	0.00	0.00	0.00
12	0.47	0.00	2.12	0.59	1.06	1.18	12.48	15.52	2.59	1.41	0.00
13	6.09	16.31	5.06	2.18	0.23	0.23	20.11	34.72	35.43	6.34	0.46
14	0.22	0.00	0.00	0.11	9.16	9.16	19.78	1.81	17.32	0.00	0.00
15	0.00	0.00	0.00	24.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	29.66	1.05	0.00	0.00	1.40	0.12	0.00	0.00	0.00
17	0.74	0.00	14.65	0.00	1.35	0.00	27.09	2.22	41.12	0.00	0.00
18	0.00	0.00	0.00	14.34	2.07	0.00	0.00	0.00	0.49	0.49	0.00
19	0.00	0.00	0.00	0.10	0.00	2.06	0.00	0.00	0.00	17.55	0.00
20	14.36	1.65	0.21	0.52	0.00	0.00	0.10	0.00	0.00	1.24	0.00
21	0.00	0.00	0.00	30.14	0.00	0.00	0.00	0.00	0.00	5.14	4.80
22	0.00	0.00	0.00	1.66	0.00	0.00	0.00	0.00	0.00	0.89	65.25
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.80
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.89	36.42
25	2.76	0.00	0.00	1.96	0.00	0.00	0.00	0.36	0.00	13.87	2.40
26	0.00	0.00	0.00	0.00	0.23	0.00	0.00	100.00	0.00	2.56	0.00
27	18.60	0.00	1.16	6.24	0.00	0.00	0.00	0.00	0.00	0.21	4.23
28	5.72	40.85	0.22	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	0.68	9.57	29.49	0.00	0.11	0.00	0.68	0.00	3.83	0.45	5.18
30	7.06	24.58	41.87	10.23	1.54	0.59	5.45	0.00	0.00	0.00	0.00

Maximum availabilities of FTEs in each type are shown in Table C2.

Table C2. Upper bound on total people by type

	FTE Type1	FTE Type2	FTE Type3	FTE Type4	FTE Type5	FTE Type6	FTE Type7	FTE Type8	FTE Type9	FTE Type10	FTE Type11
Max No. of FTEs	43	55	90	69	25	48	51	66	6	48	88

Maximum availabilities of FTEs in each skill set are shown in Table C3.

Table C3. Upper bound on total people by skill set

	Group 1: Type1, Type2, Type3	Group 2: Type4, Type5, Type6, Type7	Group 3: Type8, Type9	Group 4: Type10, Type11
Max No. of People	188	179	142	131

There is a minimum required FTEs and maximum allowed FTEs set for each Thrust. Table C4 contains these values.

Table C4. Minimum and maximum allowed total FTEs for each Thrust.

Thrust	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
FTE_min_n	4	4	4	4	4	4	4	4
FTE_max_n	75	75	75	75	75	75	75	75

Thrust	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
FTE_min_n	4	4	4	4	4	4	4	4
FTE_max_n	75	75	75	75	75	75	75	75

Thrust	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
FTE_min_n	4	4	4	4	4	4	4	4
FTE_max_n	75	75	75	75	75	75	75	75

Thrust	**25**	**26**	**27**	**28**	**29**	**30**
FTE_min_n	4	4	4	4	4	4
FTE_max_n	75	75	75	75	75	75

FTE_min_{ij} and FTE_max_{ij} are 11 × 30 matrices containing the minimum required and maximum allowed FTEs of certain type for each Thrust are displayed in Table C5 and C6.

Table C5. Minimum requirements for FTEs of certain type for each Thrust, FTE_min_{ij}

Thrusts	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	0	0	0	3	0	0	0	0	0	0	8.5
2	1.5	0	0	10.5	0	0	1.5	0	0	0	1.5
3	0	0	3.5	0	0	0	0	13	2	1.5	0
4	1.5	1.5	4.5	2	1.5	1.5	3.5	1.5	6.5	1.5	0
5	5	0	1.5	3	0	0	0	0	0	0	0
6	2	1.5	12	2.5	4	2	0	0	6	8	1.5
7	1.5	0	1.5	4	0	15	1.5	0	5.5	0	0
8	5.5	0	3.5	1.5	0	0	0	0	0	0	0
9	0	0	1.5	5	0	0	2	0	0	0	0
10	2.5	4	0	2	0	1.5	0	1.5	0	2	2
11	3	7	4.5	1.5	2	1.5	1.5	0	1.5	0	0
12	0	0	1.5	1.5	1.5	1.5	4	4.5	2	1.5	0
13	2	4	2	1.5	0	1.5	6	8.5	11	2.5	1.5
14	1.5	0	1.5	1.5	2.5	3.5	5.5	1.5	4.5	0	0
15	0	0	0	6	0	0	0	0	0	0	0
16	0	0	7.5	1.5	0	0	1.5	1.5	0	0	0
17	1.5	0	2.5	1.5	1.5	0	5.5	1.5	8.5	0	0
18	0	0	0	4.5	1.5	0	0	0	1.5	1.5	0
19	0	0	0	0	0	1.5	0	0	0	3	0
20	3.5	1.5	1.5	1.5	1.5	0	1.5	0	0	2	0
21	0	0	0	4.5	0	0	0	0	0	2.5	1.5
22	0	0	0	1.5	0	0	0	0	0	1.5	13.5
23	0	0	0	0	0	0	0	0	0	0	7
24	0	0	0	0	0	0	0	0	0	2	9
25	1.5	0	0	1.5	0	0	0	1.5	0	8.5	2
26	0	0	0	0	1.5	0	0	15	0	2	1.5
27	4.5	0	1.5	2.5	0	0	0	0	0	1.5	3
28	2.5	12	0	1.5	0	0	0	0	0	0	0
29	0	2.5	8.5	0	1.5	0	1.5	0	2	1.5	2
30	3.5	6	10.5	3	1.5	1.5	2	1.5	1.5	0	0

Table C6. Maximum restrictions for FTEs of certain type for each Thrust, FTE_max_{ij}

Thrusts	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9	Type 10	Type 11
1	0	0	0	6	0	0	0	0	0	0	17
2	3	0	0	21	0	0	3	0	0	0	3
3	0	0	7	0	0	0	0	26	4	3	0
4	3	3	9	4	3	3	7	3	13	3	0
5	10	0	3	6	0	0	0	0	0	0	0
6	4	3	24	5	8	4	0	0	12	16	3
7	3	0	3	8	0	30	3	0	11	0	0
8	11	0	7	3	0	0	0	0	0	0	0
9	0	0	3	10	0	0	4	0	0	0	0
10	5	8	0	4	0	3	0	3	0	4	4
11	6	14	9	3	4	3	3	0	3	0	0
12	0	0	3	3	3	3	8	9	4	3	0
13	4	8	4	3	0	3	12	17	22	5	3
14	3	0	3	3	5	7	11	3	9	0	0
15	0	0	0	12	0	0	0	0	0	0	0
16	0	0	15	3	0	0	3	3	0	0	0
17	3	0	5	3	3	0	11	3	17	0	0
18	0	0	0	9	3	0	0	0	3	3	0
19	0	0	0	0	0	3	0	0	0	6	0
20	7	3	3	3	3	0	3	0	0	4	0
21	0	0	0	9	0	0	0	0	0	5	3
22	0	0	0	3	0	0	0	0	0	3	27
23	0	0	0	0	0	0	0	0	0	0	14
24	0	0	0	0	0	0	0	0	0	4	18
25	3	0	0	3	0	0	0	3	0	17	4
26	0	0	0	0	3	0	0	30	0	4	3
27	9	0	3	5	0	0	0	0	0	3	6
28	5	24	0	3	0	0	0	0	0	0	0
29	0	5	17	0	3	0	3	0	4	3	4
30	7	12	21	6	3	3	4	3	3	0	0

Following table is D_i which represents the "benefit function" of providing financial resources to each Thrust i ($i=1, 2, 3,\ldots,30$). Each entry contains a number between 0 and 100 signifying the fitness of each Thrust with respect to qualifying for financial resources.

Table C7. The benefit function D_i for financial resources

Thrust	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
D_i	80.79	80.27	76.12	71.14	62.49	77.19	69.30	75.64	74.57	72.56

Thrust	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
D_i	76.06	79.64	77.72	75.58	86.14	78.69	83.30	82.23	81.90

Thrust	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
D_i	69.91	81.23	100	90.89	82.30	60.14	78.66	71.51	73.07

Thrust	**29**	**30**
D_i	76.14	73.07

Y_min_n and Y_max_n are vectors of size 30 containing the minimum budget required to run the projects in each Thrust and the amount that each PG has asked for each Thrust.

Table C8. The upper and lower bound for budget allocation for each Thrust, Y_min_n *and* Y_max_n

Thrust	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Y_min_n	4	2.1	1.25	1.3	1.7	2.3	1.85	1.5	1.1	2.5
Y_max_n	8	4.2	2.5	2.6	3.4	4.6	3.7	3	2.2	5

Thrust	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Y_min_n	2	2.5	2	0.25	1	1.15	4.5	0.9	2
Y_max_n	4	5	4	0.5	2	2.3	9	1.8	4

Thrust	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Y_min_n	1.6	0.75	0.1	2.55	1.7	3.5	1.05	1.6	1
Y_max_n	3.2	1.5	0.2	5.1	3.4	7	2.1	3.2	2

Thrust	**29**	**30**
Y_min_n	0.8	1.15
Y_max_n	1.6	2.3

Assigned weights to criteria for calculation of a single score for each Thrust.

Table C9. The weights of criteria in LP model

Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Levera ge	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
0.03	0.07	0.39	0.10	0.21	0.00	0.00	0.13	0.07

Appendix D – LP Problem Formulation

LP Formulation Technique

The following are the steps taken in order to formulate the LP model in standard form (Stevenson, 2010; Darst, 1991; Eiselt and Sandblom, 2007):

1-Understanding the problem:

The goal of the DRDC annual S&T allocation problem is to assign human and financial resources to various Thrusts within DRDC that will optimize total government objective written as a single-valued linear function. The following definitions guide through the next crucial steps that define the LP model:

People type:	Specific skill a human resource possesses (11 different types)
Thrusts:	30 Thrusts, Specific focus groups with various project types
Budget	The financial resources (aside from FTEs) assigned to each Thrust

The DRDC problem can be described in the LP framework as the problem of how to distribute the constrained budget and human resources among the Thrusts in order to optimize the total sum of all projects' measured expected outcome.

2-Identifying the decision variables:

Decision variables are the factors that can be adjusted in order to improve results. They are the decisions that need to be made. In this problem, decision variables include the assignment of various types of FTEs and financial resources to Thrusts.

The following decision variables are introduced:

X_{ij} — Number of people of type j, working in Thrust i for $i=1,2,3,\ldots,30$ and $j=1,2,3,\ldots,11$

Y_i — Budget assignment to each Thrust (Millions of Dollars) for $i=1,2,3,\ldots,30$

3- Determining the LP single-valued objective function:

This step captures the mathematical relationship between decision variables and the overall goal expressed as the LP objective function. This function is a linear combination of the decision variables. Normally the business outcome is measured through financial gain. In the DRDC problem, the objective is defined by successful projects that do not return measurable monetary benefits. However, the objective is to maximize the expectation of benefit and success from the assignment of resources to Thrusts.

The resources in the DRDC problem consist of 2 categories: people and the budget. First, people, X_{ij} are designated as Full-Time Equivalents (FTE). This group refers to DRDC scientists. Secondly, the Budget resource amount, Y_i is to be spent on project-related activities. This fund is often spent on acquiring expert help from the private sector.

The following constants are introduced in the LP formulation:

C_{ij}	The "benefit function" of having people of type j acting in Thrust i (2D matrix of size: 30 ×11) in "benefit units"
D_i	The "benefit function" for assigning budget to each Thrust (Vector of size 30) in "benefit units"

Now, define the LP objective function, Z in "benefit units" that captures the compounded benefit of assigning different types of resources to Thrusts. The objective is to maximize the total benefits function as defined in the following:

$$Z = \sum C_{ij} X_{ij} + \sum D_i Y_i$$

C_{ij} and D_i are termed the "benefit function" signifying the "benefit" of assigning resources of certain type to a certain Thrust (FTEs in case of C_{ij} and budget in case of Y_i). These two matrices are the fixed components in the formula and efforts are taken to optimize X_{ij} and Y_i in order to maximize Z.

C_{ij} and D_i are computed by data available through the CMPE from the previous years' resource assignment. These data display the level of importance and profit of each Thrust that was implicitly decided by DRDC.

4-Idendifying the constraints:

Constraint equations capture the limitations that exist within the LP model with respect to the decision variables. For example, the quantity of Type-1 employees available in DRDC is limited to 140 individuals. The constraint equations can also be a linear combination of several variables. For example, the total assignment of FTEs of different types within a Thrust is limited to 75 individuals.

Constraints play a major role in the solution space. There are lower and upper bounds enforced to the number of human resources assigned to Thrusts, skill types, and budget. Constraints are critical in ruling out infeasible solutions and setting proper initial states.

a) Non-negativity of resource assignment:

$$X_{ij} \geq 0,\ Y_i \geq 0$$

The elements in matrix X represent the quantity of FTEs that are either zero or a positive number. Vector Y contains the value of DRDC funds awarded which is also constrained to be non-negative in all its values.

b) Total number of employees:

$$\sum X_{ij} \leq 640$$

In the DRDC problem, the problem is how to assign 11 types of scientists to 30 Thrusts. There are an estimated 640 scientists employed by DRDC, however, this value may change and later is the subject of sensitivity analysis.

c) Minimum and maximum number of FTEs of each type assigned to each Thrust:

$$FTE\_min_{ij} \leq X_{ij} \leq FTE\_max_{ij}$$

The Thrusts submit proposals for their operational requirements in terms of the number of scientists required of each type. This is translated to the FTE_max_{ij} matrix. Due to resource limitations, not all Thrusts are awarded what they had requested. However, they are guaranteed a minimum percentage of what their proposal requests. FTE_min_{ij} will contain the quantities that the model assigns to each Thrust as a minimum. Note that both minimum and maximum constraints are presented in 2D matrices of size 30×11.

d) Minimum and maximum of total FTEs in each Thrust:

$$FTE\_min_n \leq \sum X_{nj} \leq FTE\_max_n \qquad (1 \leq n \leq 30)$$

Restrictions are imposed on total FTE assignment to each Thrust (i.e., the total number of different scientist types assigned). This value is estimated from available data and managerial experience.

e) Maximum number of FTEs available capable of each skill type:

$$\sum X_{im} \leq FTE\_type\_max_m \qquad (1 \leq m \leq 11)$$

The expression above sets the limits on how many scientists available that are capable of being of each type. Since an FTE is capable of being assigned to different types, *FTE_type_max* can be up to 640 for each type.

f) FTEs with multiple skills:

An individual scientist as FTE can be associated with different and multiple types of skills. If total FTEs are 640, then the sum of all types available is more than 640. Therefore there will be additional constraints for the sum of certain types.

For instance if there are 3 individuals in the resource base, and there are 5 different types of skills, then suppose the capabilities of each individual are as follows:

Individual 1: Type1, Type3, Type4
Individual 2: Type2, Type3, Type4
Individual 3: Type3, Type4, Type5

Then the total availabilities are as follows:

Type1	Type2	Type3	Type4	Type5
1.0	1.0	3.0	3.0	1.0

Which totals 9 units (1+1+3+3+1) of 5 different types utilizing only 3 individuals.

If individual 1 has been completely assigned to a Thrust, then the remaining availability, after removing individual 1 becomes as follows:

Type1	Type2	Type3	Type4	Type5
0	1.0	2.0	2.0	1.0

Which totals 6 (0+1+2+2+1) units of 4 different types utilizing 2 individuals.

The scientific skills in FTEs can be divided into four groups in the DRDC problem with similar skill sets among the 11 people types. Table D1 summarizes a possible grouping of skill types based on their similarities. An FTE belonging to each group possesses the skills listed for that group and his/her time can be divided doing different or the same tasks between Thrusts.

Table D1. Categories of skill types within scientific FTE group (Source: DRDC, 2011b)

Groups	Skill Set
Group 1 (Types 1, 2,3)	• Command and Control Information Systems Performance • Communications Networks • Intelligence, Surveillance and Reconnaissance
Group 2 (Types 4,5,6,7)	• Complex Systems • System Autonomy • Mobile Systems • Weapons Systems
Group 3 (Types 8,9)	• Personnel Protection • Protection of Assets
Group 4 (Types 10,11)	• Human Systems Integration • Behavioural Effects

This will introduce another set of constraints to include in the LP model as follows:

Group 1: $\sum X_{ij} \leq FTE\_type\_Group1\_max \quad (1 \leq j \leq 3)$

Group 2: $\sum X_{ij} \leq FTE\_type\_Group2\_max \quad (4 \leq j \leq 7)$

Group 3: $\sum X_{ij} \leq FTE\_type\_Group3\_max \quad (8 \leq j \leq 9)$

Group 4: $\sum X_{ij} \leq FTE\_type\_Group4\_max \quad (10 \leq j \leq 11)$

g) Maximum budget available (Millions of Dollars):

$$\sum Y_i \leq Total\_Budget$$

This budget refers to the DRDC funds which are awarded to Thrusts in order to be spent on external resource procurement and other research expenses. The total budget for fiscal year 2009-2010 was ~$30M and for 2010-2011 was ~$34M.

h) Minimum and maximum amount given to each Thrust:

$$Y\_min_i \leq Y_i \leq Y\_max_i$$

The constraint above is extracted from the proposals for resources where Y_max_i is the amount asked for by each Thrust. At this point, the fact that sometimes more funds are directed towards some Thrusts to meet certain objectives is ignored (and the limit strictly applied).

The above formulae and constraints are used to model the linear programming structure of the DRDC problem to build upon and expand to capture the reality of DRDC's problem. Appendix C-"Linear Programming Data Elements" provides a detailed description of the LP data presented above in matrix format.

5-Determining appropriate values for parameters:

The relationship between various skill types and their value to each Thrust (matrix C_{ij}) and the benefit of applying financial resources to each Thrust (vector D_i) need to be determined. To construct the initial set of data for C_{ij} and D_i the data from previous years are utilized to model the historical resource distribution among Thrusts. This information provides what management decided on previously for types and resources to Thrusts. The relationship extracted from previous data is acknowledged as a combination of Thrust evaluations, as well as management's discretion. The data from previous years are also utilized as a possible means of guiding the LP results through the solution space.

LP Related Data

DRDC, through its database, Collaborative Planning and Management Environment (CPME), tracks all of the R&D projects. CPME is DRDC's enterprise resource planning tool used to manage internal resources as well as track external leveraging and international activities (Wheaton and Bayly, 2010).

All project managers provide regular updates through CPME. All resource-related details about the projects are accessible and can be verified. The CPME is the only source of project-related information with which this research works. The data for two successive fiscal years (2009-2010 and 2010-2011) are used to construct elements of the LP model.

There are two categories of data provided by CPME. The first category relates to the project specifics such as start and end date, DRDC and DND funds and the quantity of various FTE types involved along with their cost. The second group of data relates to the 9 scores given by management to the projects. The criteria include:

1. Alignment to Hard Problems,
2. Project Originality,
3. Exploitation Plans,
4. Potential for Uptake,
5. Project Scope,
6. Schedule Management,
7. Budget Management,
8. Leverage and

9. Overall Quality.

These data elements are drawn from DRDC's Performance Management Framework (PMF). There are multiple LP model elements that need to be defined or extracted from the CPME data. These include:

1. the benefit function for FTE assignment (C_{ij});
2. the benefit function for DRDC fund distribution (D_i);
3. the constraint values for multiple FTE upper and lower bounds
4. the constraint values for fund allocation
5. the various Thrust related data required to set up the model as noted above.

Applicable data from CPME were selected by DRDC and communicated in MS-Excel sheets. Next, the steps to obtain the C_{ij} and D_i are explained.

Computing the benefit functions

As formulated earlier, the LP model relies on matrices C_{ij} and D_i which are termed the benefit functions. They contain the relative benefit to DRDC and the Government of Canada of applying different resources to various Thrusts. The scores provided by management is a meaningful measure that can define a Thrust's overall value. Let us define the benefit matrix C_{ij} as a function of Thrust scores, such that

$$C_{ij} \propto Weighted\_Thrust\_Scores_{ik}$$

However, not all criteria have the same importance. For example, "Alignment to Hard Problems" is considered more important compared to "Project Originality". The weight of each score needs to be determined in order to draw an accurate picture of the implicit system. Therefore, the overall Thrust scores are obtained through the weighted average of scores for individual criteria, as follows:

$$Weighted\_Thrust\_Scores_{ik} = Weights_k \times Thrust\_Scores_{ik}$$

$Weights_k$ contains the weighting scheme for the criterion k. The result of the above equation is a vector with a scalar value representing the score of each Thrust. However, C_{ij} is expected to represent the value of different FTE types for each Thrust. There are 11 different FTE types which might have different values for different Thrusts. Therefore, it is required to create a function that produces this two dimensional matrix.

Another set of information is the FTE assignment of the 2009-2010 fiscal year. This matrix is an indication of the Thrust requirements for FTEs and what FTE types are assigned that were deemed more beneficial. This matrix contains the resources requested by Thrusts each year prior, and requirements will be different in the new fiscal year. However, in our LP formulation, this fact has already been accounted for through minimum constraint settings for FTE assignment for each Thrust. This minimum constraint is based on the request placed forward by each Thrust.

Considering the above argument, the C_{ij} function is defined as follows:

$$C_{ij} \propto X_{(2009\text{-}2010)\ ij} \times Weights_k \times Thrust\_Scores_{(2009\text{-}2010)\ ik}$$

Now, the 2D matrix values correspond to 11 FTE types and 30 Thrusts. Each value in the matrix represents the benefit of allocating an FTE of a certain type to a particular Thrust.

To determine the value of C_{ij}, the only unknown is the weights of the scores, $Weights_k$. The LP is used to establish the relationship between the ratings of the projects in fiscal year 2009-10 and resource assignments. Going back to the CPME, results are available for two consecutive fiscal years. Therefore, one sample solution is available that can be useful in order to determine the weighting scheme for the criteria. Looking at the LP formulation, the objective is to maximize the following function:

$$\text{Maximize } X_{(2010\text{-}2011)\,ij} \times C_{ij}$$
$$= X_{(2010\text{-}2011)\,ij} \times (X_{(2009\text{-}2010)\,ij} \times Weights_k \times Thrust\_Scores_{(2009\text{-}2010)\,jk})$$

The data provide the FTE allocation for two consecutive years in addition to the Thrust scores. Therefore the only unknown remaining in the above formula is the weighting scheme of the scores, $Weights_k$.

In order to solve the above maximization problem, the constraints surrounding the weights of the score need to be defined. They should all be greater than zero and less than 1, and they should sum up to 1. Solving for the above equation in the LP will not result in a realistic weighting scheme because the constraints are not known or well defined. Therefore the values for the score weights are estimated using a more direct relationship between the discussed elements. If it is assumed that the $X_{(2010\text{-}2011)\,ij}$ is the result of $X_{(2009\text{-}2010)\,ij}$ being influenced by the benefit function C_{ij}, then using LP, the following relationship will yield values for the weights:

$$X_{(2010\text{-}2011)\,ij} = X_{(2009\text{-}2010)\,ij} \times Weights_k \times Thrust\_Scores_{(2009\text{-}2010)\,ik}$$

However, solving the above equation using CPME's raw data will not result in a solution. It must be kept in mind that the aim is to estimate the relationship between $X_{(2010\text{-}2011)\,ij}$ and $X_{(2009\text{-}2010)\,ij}$ and, in reality, such a solid relationship does not exist. Therefore some manipulations are required to smooth out the inconsistencies in the data resulting in a desirable linear relationship.

As discussed in, the following formula is used to estimate the values of score weights.

$$X_{ij2010\text{-}2011} = X_{ij\ 2009\text{-}2010} \times \text{Weights} \times \text{Thrust Scores}_{2009\text{-}2010}$$

Theoretically all the weights are the same across all Thrusts. However with great number of equations involved, this will result in infeasibility. We will solve the above equation allowing for different weights for scores in each Thrust and at the end obtain the average of weights across the 30 Thrust.

The product of scores and their pertinent weights are modified to allow up to 100% increase or decrease in the FTE assignment. Also a constraint for the total number of FTEs is implemented.

As expected of LP, the algorithm configures the variables with highest rate of return first up to the value allowed by the constraint. Considering that the only constraints that are set on the weights is the total sum (equal to one) and the individual value (between zero and one). Therefore the solution for each Thrust contains a value of one for a particular type as shown in the next table. To obtain a global weight for each score across the Thrusts, we calculate the arithmetic mean of the weight in each Thrust.

The equations are implemented in MS-Excel and What's Best! add-on was utilized to solve. 'Project Scope' and 'Schedule Management' contain weight of zero. Although this is an unrealistic outcome, we will treat this as the best estimate.

Once the criteria weights are obtained, we will use the following formula to construct the benefit function. Appendix C – Linear Programming Data Elements, contains the values for matrices C_{ij} and D_i.

Table D2. Calculations of the criteria weights for LP model

Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating - Efficient Schedule Mgt	DST's Rating - Efficient Budget Mgt	Quality DST Evaluation
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	0.00	0.60	0.00	0.40	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Arithmetic Mean								
0.03	**0.07**	**0.39**	**0.10**	**0.21**	**0.00**	**0.00**	**0.13**	**0.07**

Table D3 contains the weights for criteria that were estimated from the CPME data of 2 consecutive years. These score weights contribute to construction of the benefit function (C_{ij}) as described earlier.

Table D3. Assigned weights to criteria

Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake	Leverage	Project Scope	Schedule Mgt	Budget Mgt	Quality DST Evaluation
0.03	0.07	0.39	0.10	0.21	0.00	0.00	0.13	0.07

The benefit function for DRDC fund calculation (D_i) is taken directly proportional to the Thrust scores.

$$D_i = Weights_k \times Thrust\ Scores(2009\text{-}2010)_{ik}$$

The benefit function C_{ij} includes the initial resource assignment of FTEs. However, in the D_i calculations, the budget allocation of 2009-10 fiscal year was ignored. This decision was taken after studying the amounts of DRDC funds in both fiscal years. The values were not consistent enough to make logical conclusions on their possible relationship. However, based on the current practice at DRDC, the amount of DND funds influence the decision for DRDC fund allocation.

Appendix C–"Linear Programming Data Elements", contains the computed values for the C_{ij} and D_i matrices. The data from CPME, covering two consecutive fiscal years was used to calculate the missing component in the LP formula, which were the weights for criteria scores in CPME. Now the LP framework is complete and ready to find an optimum solution for resource allocation. However, in the above computations, the Thrust scores yet to be defined. Through CPME, scores for projects were provided, but in the LP formulation, Thrust scores are utilized. The following pages discuss the steps to compute scores for Thrusts.

Computing Thrust scores

In computing the benefit function above, Thrust scores are taken into consideration. However, the scores provided in CPME for criteria in are for the individual projects. The LP model requires the scores at the Thrust level. Thus, there is a need to convert Project scores to values that capture the quality of each Thrust with respect to the nine criteria. For example, Table D4 displays the score values for Projects 1 to 9 attributed to Thrust 1. The arithmetic mean is used to compute the average of the scores of the projects for each criterion for that Thrust. These mean values could be used to represent the scores for Thrust 1.

Table D4. Average score for criteria for Thrust 1 by arithmetic mean

	Alignment - Hard Problems	Project Originality	Exploitation Plan?	Potential for uptake of deliverable - Stakeholder Commitment	Leverage DST Rating	Project Scope	DST's Rating (Efficient Schedule Mgt)	DST's Rating (Efficient Budget Mgt)	Quality DST Evaluation
Project1	5	4	0	3	3	5	5	5	5
Project2	4	4	5	5	5	4	4	5	4
Project3	4	4	0	4	3	4	4	5	5
Project4	5	3	0	3	4	5	3	5	3
Project5	5	5	5	3	4	4	3	5	4
Project6	4	3	0	3	3	3	3	5	3
Project7	4	4	5	4	3	5	3	5	4
Project8	4	3	0	3	3	1	1	5	2
Project9	5	4	0	2	3	3	1	5	3
Average scores for Thrust 1	4.44	3.78	1.67	3.33	3.44	3.78	3	5	3.67

There are 3 main methods to produce an average for each criterion for the projects within a Thrust, which are mean, median and mode.

These different statistical single point measures are applied to Project scores to yield representative Thrusts scores depending on the characteristics of the data. In order to select between the choices of which measure is most relevant here, further processing of the data and analysis of their distribution is required. Appendix A–"CPME Data Analysis", contains the data analysis and tables of the mean, median and mode score values attributed to each Thrust.

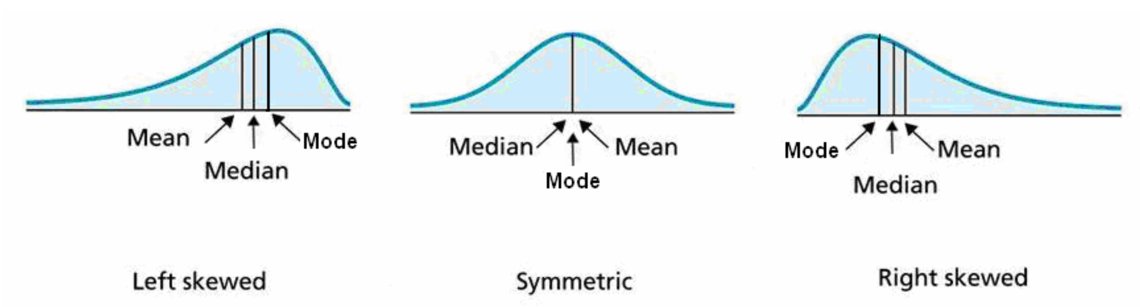


Figure D1. Types of distribution functions (Source: Weiss, 1999)

As shown in Figure D1, when the distribution (i.e., of Project scores for a single Thrust) is right-skewed, the values are concentrated at the left. In this case the mean is located to the right of both median and mode. Whereas, when the distribution is left-skewed and values are more concentrated to the right, the mean is located to the left of both median and mode. Similarly, the mode is greatly influenced by the high frequency of a single value while the mean is affected by extreme values. To avoid these difficult responses when score distributions are skewed, the median (which is less affected) is often considered as a less biased single point measure. The median is between the mean and mode measures, and is considered to dampen the effects of both frequency and extremity of data (Levin, 1987 and Berenson et. al, 1988).

Table D5 contains the mean and standard deviation for the scores in each category across all projects. These values are calculated based on all the raw data at the Project level from CPME. However, the 'Exploitation Plan' is marked as a Yes/No and the mean is calculated as the ratio of 'Yes' scores (=1, otherwise 0) to the total number of projects.

Table D5. Mean and standard deviation of Thrust scores

	Hard Problems	**Project Originality**	**Exploitation Plan**	**Potential for uptake**	**Leverage**	**Project Scope**	**Schedule Mgt**	**Budget Mgt**	**Quality**
Mean	3.71	3.64	0.46	3.28	3.19	3.75	3.81	4.78	3.12
Standard deviation	0.50	0.32	0.50	0.65	0.75	0.45	0.50	0.27	0.42

There are 3 categories of distributions detected in the data. The first group of data are slightly left-skewed as displayed in Figure D2 for alignment to "Hard Problems". For this case, the Project scores distribution graph is not completely symmetrical. Weiss (1999) indicates that it is not necessary to insist on precise symmetry to classify a distribution as normal and to assume normality in functional form. Therefore, in cases like Figure D2, the mean is used for this group of project scores to calculate a representative score value for each Thrust. The variables deemed slightly left skewed are Hard Problems, Originality and Schedule Management.

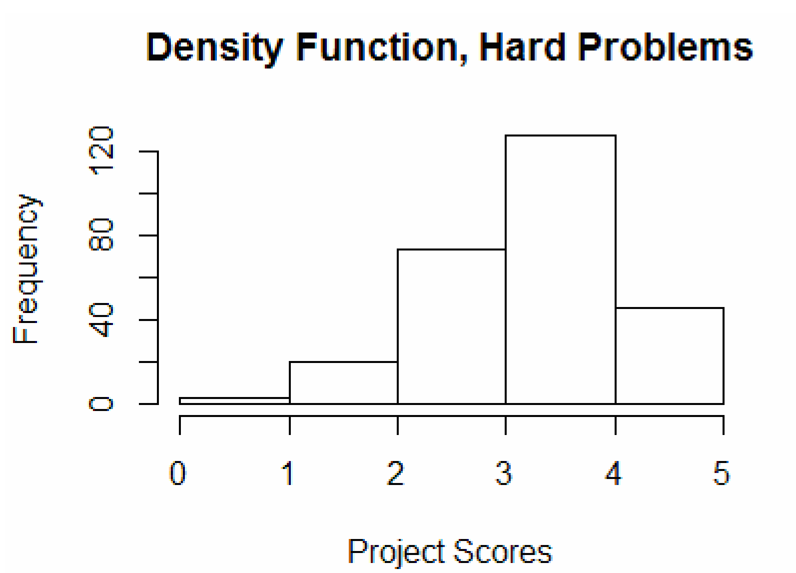


Figure D2. Distribution function for "Hard Problems" criterion Project scores (Source: DRDC, 2011b).

The calculated values for mean, median and mode for these criteria are shown in Table D6.

Table D6. Values of mean, median and mode for left-skewed data of scoring criteria

Criteria	Mean	Median	Mode
Alignment to Hard Problems	3.7185	4	4
Originality	3.6814	4	4
Schedule Management	3.7888	4	4

The second class of distributions detected in the data are normal. Figure D3**Figure** displays the distribution function for “Potential for Uptake”. Therefore, in cases like Figure D3, the mean is used for this group of project scores to calculate a representative score value for each Thrust.

Other groups of data that demonstrate the same characteristics as Potential for Uptake are Quality and Leverage.

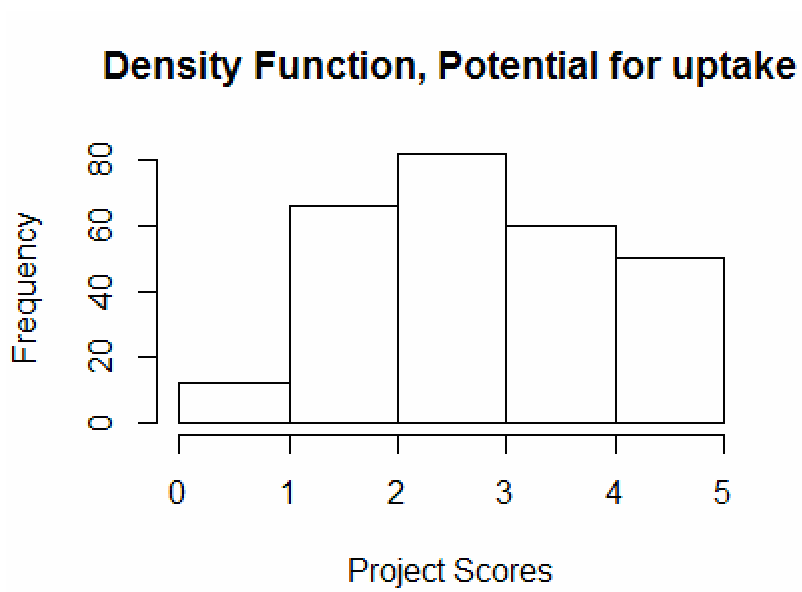


Figure D3. Near symmetric distribution function of “Potential for Update” criterion Project scores (Source: DRDC, 2011b)

Table D7 shows close values of the corresponding means, medians and modes for the near-symmetric criteria Project scores. In this case, the mean value is selected to calculate the single point score for each Thrust.

Table D7. Values of mean and median for near-symmetric data of scoring criteria

Criteria	**Mean**	**Median**	**Mode**
Potential for Uptake	3.2593	3	3
Quality	3.1407	3	3
Leverage	3.3222	3.5	4

The last group that displays definite skewness includes Budget Management and Scope. Figure D4 shows the extremely left-skewed plot.

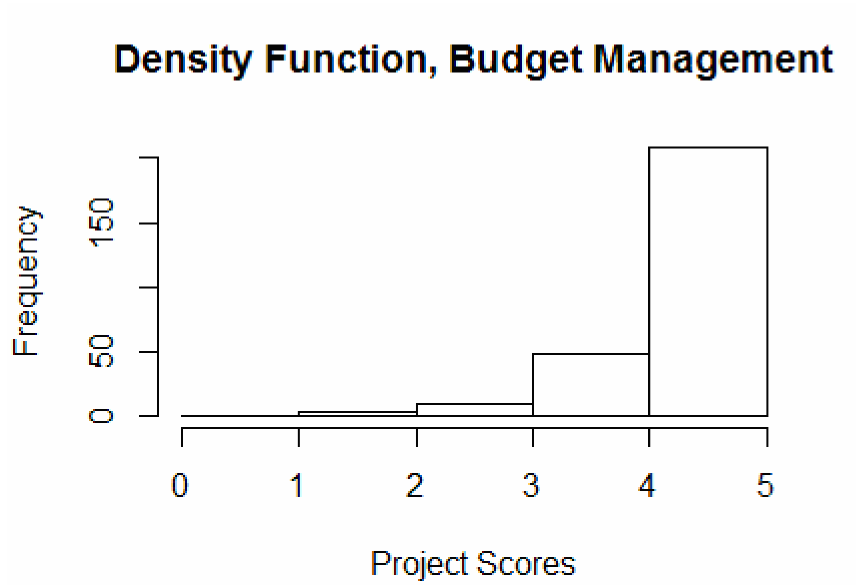


Figure D4. Distribution function for "Budget Management" criterion Project scores (Source: DRDC, 2011b)

Feedback from DRDC indicates that this is quite normal for Budget Management distribution across Project as this criterion is always dealt with diligently and monitored to ensure compliance by all projects. Given the skewed distribution, the median value is used for the Budget Management and Scope criteria Project scores to compute an average value for Thrusts. Values of mean, median and mode for Budget Management and Scope are displayed in Table D8.

Table D8. Mean and Median of left-skewed data

Criteria	**Mean**	**Median**	**Mode**
Budget Management	4.7256	5	5
Scope	3.7548	4	4

The Exploitation Plan is a unique criterion as it contains only Boolean values. Arithmetic mean can be calculated by dividing the total number of 'Yes' scores by the total number of projects. However, the median and mode values for Exploitation Plan are found to be zero.

Finally, Table D9 captures the values of the nine Project scoring criteria assigned to each Thrust in the formulated LP model. The "Overall Score" is calculated based on identical weighting of the criteria. The 'Overall Score' is the average of all 9 scores by Thrusts.

Table D9. Thrusts scores for 2009-10 (combined) based on the single point measures from the distribution of Project scores by Thrust.

Thrust	Hard Problems	Project Originality	Exploitation Plan	Potential for uptake	Leverage	Project Scope	Schedule Mgt	Budget Mgt	Quality	Overall Score
1	4.44	3.78	0.33	3.33	3.44	4.00	3.00	5.00	3.67	3.59
2	4.00	3.93	0.41	3.53	2.80	4.00	3.07	4.00	3.73	3.46
3	4.00	3.75	0.29	3.17	3.33	4.00	3.83	5.00	3.25	3.53
4	3.90	3.40	0.17	3.10	3.30	3.50	4.20	5.00	3.00	3.36
5	3.29	3.43	0.00	3.00	2.14	3.00	3.29	5.00	2.86	2.89
6	3.63	3.63	0.47	3.94	3.69	3.00	3.19	5.00	3.25	3.52
7	2.60	3.20	0.45	3.80	3.20	4.00	3.00	5.00	2.80	3.32
8	3.33	3.83	0.43	2.67	2.00	4.00	4.50	5.00	3.17	3.40
9	4.67	3.00	0.00	4.67	1.33	3.00	3.67	5.00	3.33	3.19
10	3.43	4.14	0.11	3.29	2.71	5.00	4.57	5.00	2.71	3.49
11	3.86	4.00	0.31	3.43	3.57	4.00	4.14	5.00	2.57	3.57
12	3.78	3.56	0.54	3.89	2.00	4.00	4.11	5.00	2.67	3.52
13	4.11	3.89	0.26	3.39	4.33	4.00	4.22	4.00	3.28	3.62
14	3.78	3.89	0.45	3.11	3.11	4.00	3.56	5.00	2.56	3.48
15	3.75	3.50	0.75	3.75	2.75	4.00	4.25	5.00	3.50	3.81
16	4.00	4.00	0.45	3.40	3.40	4.00	3.70	5.00	2.90	3.63
17	3.91	3.73	0.55	3.73	4.45	4.00	3.91	5.00	3.55	3.89
18	3.00	3.67	1.00	2.67	3.50	5.00	3.83	4.50	2.50	3.74
19	3.13	3.38	1.00	2.50	4.00	4.00	4.38	5.00	2.38	3.75
20	3.25	3.50	0.44	2.38	3.13	3.00	3.50	4.00	3.00	3.11
21	4.00	3.00	0.67	3.60	3.60	4.00	3.60	5.00	2.80	3.66
22	4.50	3.88	1.00	4.50	3.38	4.00	4.00	5.00	4.13	4.27
23	3.50	3.25	1.00	4.25	3.25	4.00	4.00	5.00	3.75	4.00
24	2.90	3.50	1.00	3.60	3.70	3.00	4.20	5.00	3.00	3.77
25	3.00	3.10	0.09	2.10	2.30	3.00	4.40	5.00	3.00	2.93
26	3.86	3.64	0.47	2.43	3.86	4.00	4.57	5.00	3.21	3.66
27	4.00	3.88	0.11	2.75	2.63	4.00	3.25	5.00	3.38	3.27
28	4.43	4.14	0.22	2.43	2.57	2.00	4.00	5.00	3.14	3.20
29	3.50	3.75	0.46	2.50	4.13	5.00	2.88	5.00	3.00	3.56
30	3.82	4.00	0.43	3.55	4.09	4.00	3.45	5.00	3.45	3.72

Selecting projects within Thrusts

There are two sets of data available which are for fiscal years 2009-2010 and 2010-2011. All Projects listed in the CPME have a start and end date. It is observed that some projects are listed in 2009-2010 that are not present in 2010-2011, and vice versa. Two ways for selecting projects within Thrusts (to calculate an overall score in each category for each Thrust) are investigated next.

There are 429 Projects listed for the 2009-2010 fiscal year and 114 are initially eliminated because of missing ranking information, project details, or both. For the first set of analysis, only a set of projects are chosen that are continued to the second fiscal year, a total of 270 projects. This will allow specific analysis of the influence of performance scores in resource assignments in the second year for the ongoing projects.

Figure D5 displays the allocated DRDC funds to the ongoing Thrusts based on total project funding in both fiscal years along with their scores in 09-10.

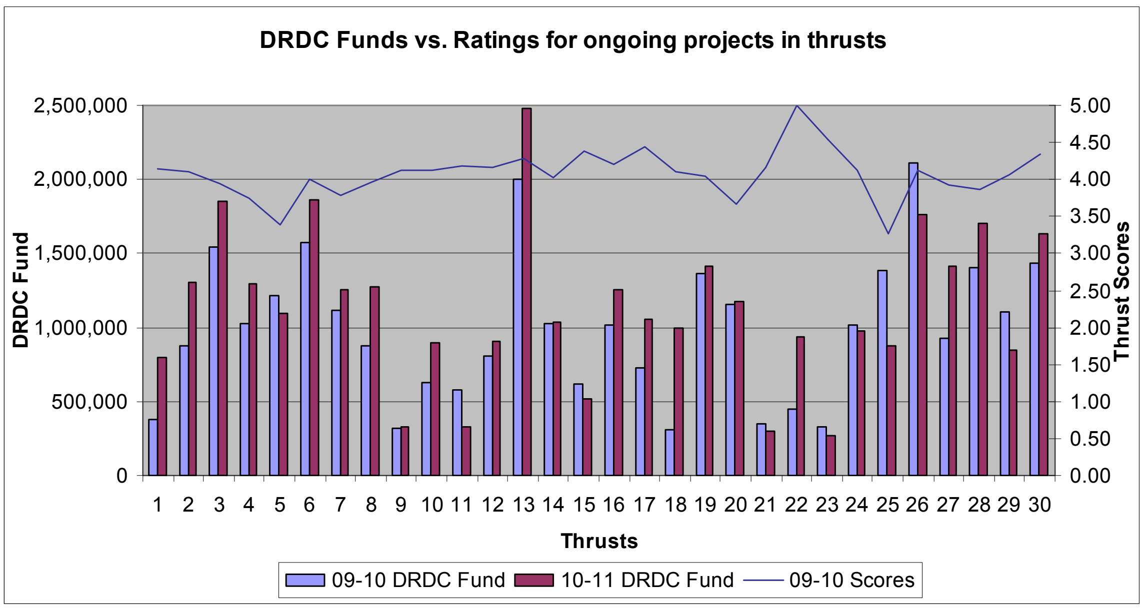


Figure D5. DRDC funds in 09-10 and 10-11 versus ratings in 09-10, ongoing projects (Source: DRDC, 2011b)

Next, the data for all the projects involved are evaluated. This time, the new projects introduced in 2010-11, as well as completed projects in 2009-10 are taken into account, a total of 315 projects. Figure D6 displays the DRDC fund for 2009-2010 and 2010-2011 with the Thrust scores 2009-2010. The Thrust scores are calculated as the mean of project scores within each Thrust, with equal weights assigned to each score.

The graph in Figure D6 shows little difference compare to Figure D5. The relative rise and fall of the funds over the two years is almost identical to when only ongoing projects were considered in Figure D5.

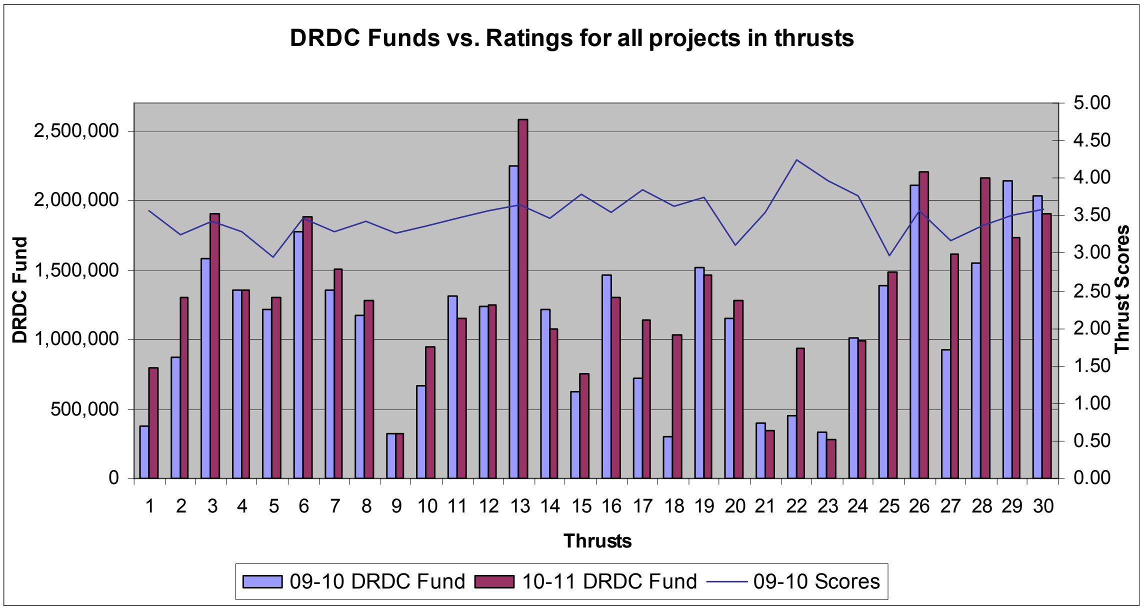


Figure D6. DRDC funds over 09-10 and 10-11 versus ratings in 09-10 for all projects (Source: DRDC, 2011b)

Looking at the analysis of the data displayed in Figure D5 and Figure D6, there is not a consistent pattern between ratings and resources. The expectation is that with good ratings, both FTE and DRDC funds must increase or stay the same, but it is not always the case. The reason they could stay the same is that Thrusts might not ask for more funds or human resources. The quantities must always be in the context of what the requested amounts are. Also, there are some Thrusts in 2010-2011 with FTE types that were not part of the program in 2009-2010 and vice versa.

This can be explained by the change in project requirements as the project goes through its phases. This should correct itself as the proposals by each Thrust indicating their FTE and fund requirements are taken into account. This information is considered in the LP formulation as constraints with upper values of each resource (*FTE_max*) and lower limits for each Thrust (*FTE_min*). Therefore, if there are requirements for new FTE types for certain Thrusts, it can be taken into account. However, the current trend in the resource assignment is a mix of the ratings as well as management's judgment which are translated into decisions for Thrusts.

Another factor that can contribute to the value of Thrust scores is the importance of each scoring criteria. The graphs in Figure D5 and Figure D6 are calculated with the assumption that all scoring criteria are equally important. However, in reality, this is not the case. This will indicate that some weighting of the criteria must be included. For example, the consensus among DRDC managers is that "Alignment to Hard Problems" is one of the more important criteria. The idea here is to adjust the weighting of each criterion in order to explain the variation of resources from one year to another.

The LP problem is solved using the data for ongoing Projects. However, the assumption here is that other new Projects do not have effects on existing ones. But in reality, every year some projects expire and new projects are introduced. Some new projects might be deemed more important and draw away resources from others. In other words, our assumptions taken to simplify the relationships can be misleading.

Appendix E – LP Solutions

In this appendix the results of LP optimization software is presented. Screen shots of the *What's Best!* report page is displayed, followed by the resource assignment tables extracted from MS Excel formula sheets which are filled out by *What`s Best!*.

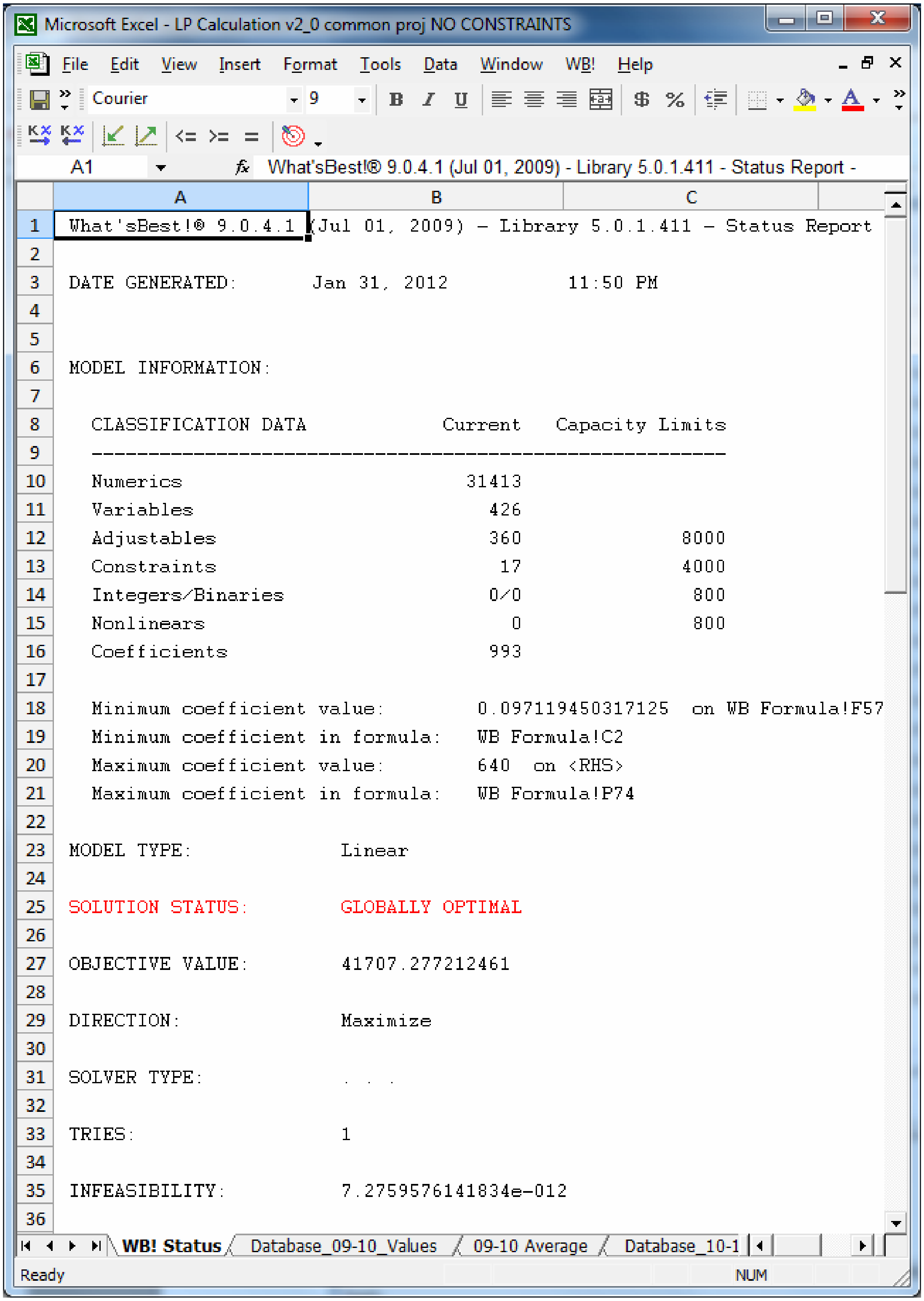


Figure E1. Output of What's Best! limited constraints

Table E1 contains the resource assignment as outputted by *What`s Best!*.

Table E1. FTE resource assignment with FTE_min and FTE_max removed

Thrusts	Type1	Type2	Type3	Type4	Type5	Type6	Type7	Type8	Type9	Type10	Type11
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0
2	0.0	0.0	0.0	61.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	1.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
5	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	48.0	0.0	0.0	0.0	0.0	0.0
8	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0
10	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	39.0	0.0	36.0	0.0	0.0
18	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	38.0	0.0
20	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.0	0.0	0.0	0.0
27	27.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	51.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table E2. DRDC fund allocation along with D_i benefit function with no constraints

Thrusts	Y_i (M$)	D_i
1	$0.00	80.23
2	$0.00	77.07
3	$0.00	75.72
4	$0.00	71.42
5	$0.00	59.30
6	$0.00	77.41
7	$0.00	72.29
8	$0.00	74.29
9	$0.00	69.64
10	$0.00	74.04
11	$0.00	79.87
12	$0.00	77.24
13	$0.00	84.14
14	$0.00	77.74
15	$0.00	85.91
16	$0.00	81.18
17	$0.00	89.41
18	$0.00	86.45
19	$0.00	88.20
20	$0.00	73.22
21	$0.00	85.35
22	$100.00	100.00
23	$0.00	91.87
24	$0.00	85.32
25	$0.00	61.44
26	$0.00	84.48
27	$0.00	72.48
28	$0.00	72.80
29	$0.00	83.37
30	$0.00	85.16

Table E3. FTE resource assignment with no constraints for Thrusts

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	71.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	105.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	84.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	24.0	0.0	72.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	89.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	70.0	0.0	0.0	0.0
27	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	59.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table E4. DRDC fund allocation along with D_i benefit function with no constraints

Thrusts	Y_i (M$)	D_i
1	$0.00	80.23
2	$0.00	77.07
3	$0.00	75.72
4	$0.00	71.42
5	$0.00	59.30
6	$0.00	77.41
7	$0.00	72.29
8	$0.00	74.29
9	$0.00	69.64
10	$0.00	74.04
11	$0.00	79.87
12	$0.00	77.24
13	$0.00	84.14
14	$0.00	77.74
15	$0.00	85.91
16	$0.00	81.18
17	$0.00	89.41
18	$0.00	86.45
19	$0.00	88.20
20	$0.00	73.22
21	$0.00	85.35
22	$100.00	100.00
23	$0.00	91.87
24	$0.00	85.32
25	$0.00	61.44
26	$0.00	84.48
27	$0.00	72.48
28	$0.00	72.80
29	$0.00	83.37
30	$0.00	85.16

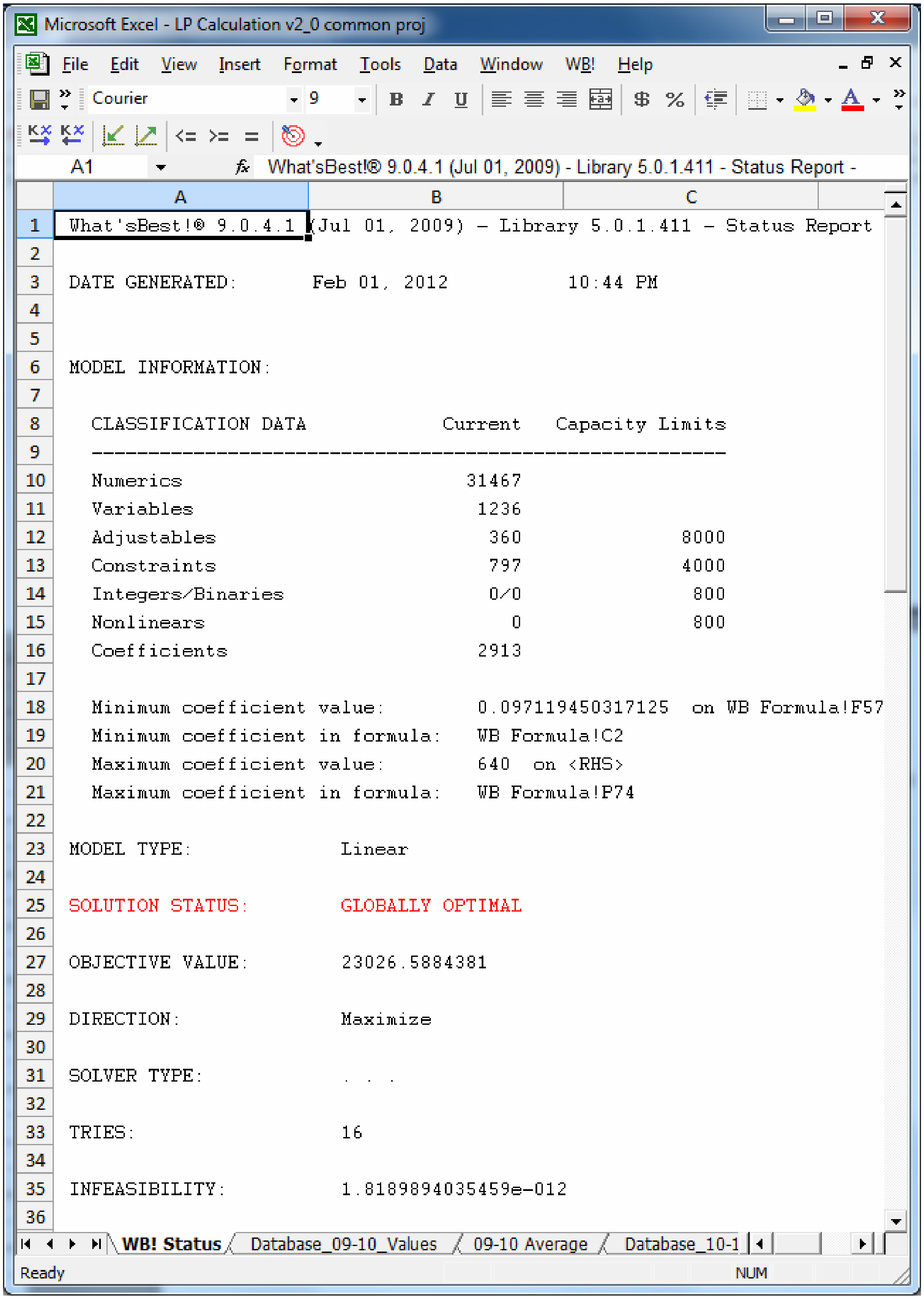


Figure E2. Solution sheet by What's Best! in MS Excel, with all constraints

Table E5. FTE resource assignment with solution with all constraints

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0
2	1.5	0.0	0.0	16.5	0.0	0.0	1.5	0.0	0.0	0.0	1.5
3	0.0	0.0	3.5	0.0	0.0	0.0	0.0	26.0	2.0	1.5	0.0
4	1.5	1.5	4.5	2.0	1.5	1.5	3.5	1.5	6.5	1.5	0.0
5	5.0	0.0	1.5	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	2.0	1.5	24.0	2.5	4.0	2.0	0.0	0.0	6.0	8.0	1.5
7	1.5	0.0	1.5	4.0	0.0	30.0	1.5	0.0	5.5	0.0	0.0
8	5.5	0.0	3.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	1.5	5.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
10	2.5	4.0	0.0	2.0	0.0	1.5	0.0	1.5	0.0	2.0	2.0
11	3.0	7.0	4.5	1.5	2.0	1.5	1.5	0.0	1.5	0.0	0.0
12	0.0	0.0	1.5	1.5	1.5	1.5	4.0	4.5	2.0	1.5	0.0
13	2.0	4.0	2.0	1.5	0.0	1.5	6.0	8.5	12.5	2.5	1.5
14	1.5	0.0	1.5	1.5	2.5	3.5	5.5	1.5	4.5	0.0	0.0
15	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	7.5	1.5	0.0	0.0	1.5	1.5	0.0	0.0	0.0
17	1.5	0.0	2.5	1.5	1.5	0.0	5.5	1.5	17.0	0.0	0.0
18	0.0	0.0	0.0	4.5	1.5	0.0	0.0	0.0	1.5	1.5	0.0
19	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	3.0	0.0
20	3.5	1.5	1.5	1.5	1.5	0.0	1.5	0.0	0.0	2.0	0.0
21	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	2.5	1.5
22	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	1.5	27.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.5
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	18.0
25	1.5	0.0	0.0	1.5	0.0	0.0	0.0	1.5	0.0	8.5	2.0
26	0.0	0.0	0.0	0.0	1.5	0.0	0.0	30.0	0.0	2.0	1.5
27	4.5	0.0	1.5	2.5	0.0	0.0	0.0	0.0	0.0	1.5	3.0
28	2.5	24.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	2.5	9.5	0.0	1.5	0.0	1.5	0.0	2.0	1.5	2.0
30	3.5	6.0	21.0	3.0	1.5	1.5	2.0	1.5	1.5	0.0	0.0

Table E6. DRDC fund allocation along with D_i benefit function taking into account the constraints

Thrusts	Y_i (M$)	D_i
1	$4.00	80.23
2	$2.10	77.07
3	$1.25	75.72
4	$1.30	71.42
5	$1.70	59.30
6	$2.30	77.41
7	$1.85	72.29
8	$1.50	74.29
9	$1.10	69.64
10	$2.50	74.04
11	$2.00	79.87
12	$2.50	77.24
13	$2.00	84.14
14	$0.25	77.74
15	$1.00	85.91
16	$1.15	81.18
17	$9.00	89.41
18	$0.90	86.45
19	$3.15	88.20
20	$1.60	73.22
21	$0.75	85.35
22	$0.20	100.00
23	$5.10	91.87
24	$1.70	85.32
25	$3.50	61.44
26	$1.05	84.48
27	$1.60	72.48
28	$1.00	72.80
29	$0.80	83.37
30	$1.15	85.16

Appendix F – LP Sensitivity Analysis for FTE Types

Table F1. Dual values for the RHS of minimum constraints on FTE types for Thrusts

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.00	0.00	0.00	-22.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	-40.02	0.00	0.00	0.00	0.00	0.00	-42.39	0.00	0.00	0.00	-36.78
3	0.00	0.00	-30.88	0.00	0.00	0.00	0.00	0.00	-38.52	-39.16	0.00
4	-40.50	-41.90	-28.93	-38.83	-41.88	-42.39	-30.82	-45.61	-17.38	-39.20	0.00
5	-26.92	0.00	-42.09	-34.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	-38.34	-41.62	0.00	-31.39	-27.78	-37.30	0.00	0.00	-34.44	-36.76	-39.71
7	-40.90	0.00	-39.83	-25.71	0.00	0.00	-40.95	0.00	-16.84	0.00	0.00
8	-18.94	0.00	-27.64	-40.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	-41.09	-31.46	0.00	0.00	-38.06	0.00	0.00	0.00	0.00
10	-34.19	-20.90	0.00	-38.81	0.00	-42.39	0.00	-44.45	0.00	-36.59	-36.36
11	-30.75	-3.03	-16.45	-42.10	-38.16	-42.39	-40.20	0.00	-45.61	0.00	0.00
12	0.00	0.00	-39.54	-41.63	-41.02	-40.87	-26.28	-25.58	-42.26	-37.89	0.00
13	-34.44	-21.28	-35.77	-39.58	0.00	-42.10	-16.51	-0.92	0.00	-31.55	-39.12
14	-41.98	0.00	-42.28	-42.24	-29.88	-29.88	-15.39	-43.14	-21.96	0.00	0.00
15	0.00	0.00	0.00	-7.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	-1.90	-40.97	0.00	0.00	-40.49	-45.45	0.00	0.00	0.00
17	-41.19	0.00	-20.71	-42.39	-40.40	0.00	-2.52	-42.34	0.00	0.00	0.00
18	0.00	0.00	0.00	-18.70	-38.98	0.00	0.00	0.00	-44.80	-38.91	0.00
19	0.00	0.00	0.00	0.00	0.00	-38.83	0.00	0.00	0.00	-9.36	0.00
20	-22.37	-39.99	-41.99	-41.68	-42.39	0.00	-42.25	0.00	0.00	-37.99	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-32.03	-32.53
22	0.00	0.00	0.00	-39.91	0.00	0.00	0.00	0.00	0.00	-38.38	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-32.87	0.00
25	-39.12	0.00	0.00	-40.15	0.00	0.00	0.00	-45.20	0.00	-23.82	-36.96
26	0.00	0.00	0.00	0.00	-42.07	0.00	0.00	0.00	0.00	-36.22	-39.71
27	-22.29	0.00	-41.03	-35.69	0.00	0.00	0.00	0.00	0.00	-39.48	-35.17
28	-35.63	0.00	0.00	-41.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	0.00	-28.56	0.00	0.00	-42.23	0.00	-41.42	0.00	-40.12	-39.07	-32.29
30	-32.55	-8.39	0.00	-28.29	-40.27	-41.58	-34.88	-45.61	-45.61	0.00	0.00

Table F2. Dual values for the RHS of maximum constraints on FTE types for Thrusts

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.62
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.12	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	35.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	45.75	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.92	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	2.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	58.22
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.34
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	90.77	0.00	0.00	0.00
27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
28	0.00	5.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.00	0.00	15.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table F3. Dual values for the adjustable cells

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	42.28	42.28	42.28	0.00	42.39	42.39	42.39	45.61	45.61	39.71	0.00
2	0.00	42.28	42.28	0.00	42.39	42.39	0.00	45.61	45.61	39.71	0.00
3	42.28	42.28	0.00	42.39	42.39	42.39	42.39	0.00	0.00	0.00	39.71
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39.71
5	0.00	42.28	0.00	0.00	42.39	42.39	42.39	45.61	45.61	39.71	39.71
6	0.00	0.00	0.00	0.00	0.00	0.00	42.39	9.33	0.00	0.00	0.00
7	0.00	42.28	0.00	0.00	41.63	0.00	0.00	45.61	0.00	39.71	39.71
8	0.00	42.28	0.00	0.00	42.39	42.39	42.39	45.61	45.61	39.71	39.71
9	42.28	41.88	0.00	0.00	42.39	42.39	0.00	45.61	45.61	39.71	37.73
10	0.00	0.00	42.28	0.00	42.39	0.00	42.39	0.00	45.61	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.61	0.00	39.71	39.71
12	41.67	42.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39.71
13	0.00	0.00	0.00	0.00	42.10	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	42.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39.71	39.71
15	42.28	42.28	42.28	0.00	42.39	42.39	42.39	45.61	45.61	39.71	39.71
16	42.28	42.28	0.00	0.00	42.39	42.39	0.00	0.00	45.61	39.71	39.71
17	0.00	42.28	0.00	0.00	0.00	42.39	0.00	0.00	0.00	39.71	39.71
18	42.28	42.28	42.28	0.00	0.00	42.39	42.39	45.61	0.00	0.00	39.71
19	42.28	42.28	42.28	42.22	42.39	0.00	42.39	45.61	45.61	0.00	39.71
20	0.00	0.00	0.00	0.00	0.00	42.39	0.00	45.61	45.61	0.00	39.71
21	42.28	42.28	42.28	0.00	42.39	42.39	42.39	45.61	45.61	0.00	0.00
22	42.28	42.28	42.28	0.00	42.39	42.39	42.39	45.61	45.61	0.00	0.00
23	42.28	42.28	42.28	42.39	42.39	42.39	42.39	45.61	45.61	39.71	0.00
24	42.28	42.28	42.28	42.39	42.39	42.39	42.39	45.61	45.61	0.00	0.00
25	0.00	42.28	42.28	0.00	42.39	42.39	42.39	0.00	45.61	0.00	0.00
26	42.28	42.28	42.28	42.39	0.00	42.39	42.39	0.00	45.61	0.00	0.00
27	0.00	42.28	0.00	0.00	42.39	42.39	42.39	45.61	45.61	0.00	0.00
28	0.00	0.00	42.03	0.00	42.39	42.39	42.39	45.61	45.61	39.71	39.71
29	41.31	0.00	0.00	42.39	0.00	42.39	0.00	45.61	0.00	0.00	0.00
30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39.71	39.71

Appendix G – LP Results Analysis

Solution with limited Constraints

The logic behind the LP algorithm is to place resources where most benefit is gained. This is displayed with our model solved in *What's Best!* with some constraints being removed from the original complete formulation of Section 3.3. Table G1 below isplays a feasible solution with limited constraints where the minimum and maximum restrictions on specific type assignment have been eliminated.

Table G1. LP limited constraints solution of FTE resource assignment by type with FTE_min and FTE_max restrictions removed

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0
2	0.0	0.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0
5	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
6	0.0	0.0	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	0.0	0.0	0.0
8	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0
10	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0	0.0
18	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0
20	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	0.0	0.0	0.0
27	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	55.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	28.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The results indicate that each of the 30 Thrusts is assigned a minimum of 4 and maximum of 75 FTEs in this model run, as per the Thrust constraints. As well, the FTE resources are assigned to the FTE Type/Thrust combination that yields the highest benefit value in the objective function matrix C_{ij}. The LP algorithm only assigns one FTE type to each Thrust because allocating FTEs of other types with equal or lower benefit does not improve the objective function. However, in Table G1, Thrust 5 has its minimum share made up of two different FTE types. This is caused by the constraints of the FTEs of multiple skill types (section 3.3 LP Formulation, constraint number 6).

Next, LP results for the model with the constraints removed on the limits for total FTE assignment for each Thrust. These results are displayed in Table G2.

Table G2. FTE resource assignment with no constraints for Thrusts

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	111.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	99.0	0.0	0.0	0.0	0.0	0.0
8	14.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	109.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	115.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	63.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Comparing Table G1 and Table G2 above, it is evident that the resources tend to concentrate on cells with the highest value in the corresponding cell in C_{ij}, the component of the benefit function. The only constraint in Table G2 is the number of available FTEs in different types. The value of the objective function for results of Table G1 (limited constraints) is 58,119 benefit units, and for results of Table G2 (no constraints) is 63,891 benefit units. Thus, the Z value has increased as expected.

In Table G2, there are 21 Thrusts that have no FTEs assigned to them. The Thrusts with lowest assigned FTEs in Table G1 (who have lower benefit value) are the first to lose their resource allocations in the LP calculations with no constraints of Table G2. Once again only one type is awarded to each Thrust, i.e., the type with the highest benefit value.

Constrainted Problems Solutions

The results of the LP models with all the pertinent constraints that were introduced are presented next. Table G3 displays the results of the solution copied from *What's Best!* in MS-Excel for the fully constrained problem as defined in Section 3.3.

Table G3. LP constrained solution FTE resource assignment by Thrusts and FTE Type

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0
2	1.5	0.0	0.0	12.0	0.0	0.0	1.5	0.0	0.0	0.0	1.5
3	0.0	0.0	3.5	0.0	0.0	0.0	0.0	26.0	2.0	1.5	0.0
4	1.5	1.5	4.5	2.0	1.5	1.5	3.5	1.5	6.5	1.5	0.0
5	5.0	0.0	1.5	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	2.0	1.5	24.0	2.5	4.0	2.0	0.0	0.0	6.0	8.0	1.5
7	1.5	0.0	1.5	4.0	0.0	30.0	1.5	0.0	5.5	0.0	0.0
8	5.5	0.0	3.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	1.5	5.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
10	2.5	4.0	0.0	2.0	0.0	1.5	0.0	1.5	0.0	2.0	2.0
11	3.0	7.0	4.5	1.5	2.0	1.5	1.5	0.0	1.5	0.0	0.0
12	0.0	0.0	1.5	1.5	1.5	1.5	4.0	4.5	2.0	1.5	0.0
13	2.0	4.0	2.0	1.5	0.0	1.5	6.0	8.5	12.5	2.5	1.5
14	1.5	0.0	1.5	1.5	2.5	3.5	5.5	1.5	4.5	0.0	0.0
15	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	7.5	1.5	0.0	0.0	1.5	1.5	0.0	0.0	0.0
17	1.5	0.0	2.5	1.5	1.5	0.0	5.5	1.5	17.0	0.0	0.0
18	0.0	0.0	0.0	4.5	1.5	0.0	0.0	0.0	1.5	1.5	0.0
19	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	3.0	0.0
20	3.5	1.5	1.5	1.5	1.5	0.0	1.5	0.0	0.0	2.0	0.0
21	0.0	0.0	0.0	9.0	0.0	0.0	0.0	0.0	0.0	2.5	1.5
22	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	1.5	27.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.5
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	18.0
25	1.5	0.0	0.0	1.5	0.0	0.0	0.0	1.5	0.0	8.5	2.0
26	0.0	0.0	0.0	0.0	1.5	0.0	0.0	30.0	0.0	2.0	1.5
27	4.5	0.0	1.5	2.5	0.0	0.0	0.0	0.0	0.0	1.5	3.0
28	2.5	24.0	0.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	2.5	9.5	0.0	1.5	0.0	1.5	0.0	2.0	1.5	2.0
30	3.5	6.0	21.0	3.0	1.5	1.5	2.0	1.5	1.5	0.0	0.0

Comparing the results of the fully constrained LP solution decision variables of Table G3 with those of Table G1 and Table G2, it is observed that the complete LP model solution is more distributed across the FTE Types and Thrusts, satisfying all the constraints for minimum and maximum Thrust allocations, and minimum and maximum FTE allocations by type. It answers to the minimum needs of all Thrusts as specified and places the remainder of resources where most benefit is obtained up to the specified maximums.

Table G4 also displays the same trend in DRDC funds allocation based on the funds minimum and maximum constraints by Thrusts. Thrust 1 is the only Thrust that its share is intermediate ("Inter"), i.e., somewhere between its requested fund and the minimum guaranteed allocation. All the rest either have received the minimum or have been awarded the amount they requested.

Table G4. DRDC funds allocation, Y_i and D_i benefits function by Thrusts *i* from the fully constrained LP problem

Thrusts	Y_i (M$)	D_i	Min/Inter/Max
1	0.55	301.11	Inter
2	0.75	292.96	Min
3	0.85	277.96	Min
4	1.00	254.30	Min
5	0.75	192.00	Min
6	2.00	328.31	Max
7	1.50	306.04	Max
8	0.80	276.24	Min
9	0.25	198.00	Min
10	0.65	231.10	Min
11	0.25	291.86	Max
12	1.20	303.92	Max
13	1.50	295.76	Min
14	1.30	305.08	Max
15	0.75	366.75	Max
16	1.50	316.74	Max
17	1.30	362.45	Max
18	1.30	401.50	Max
19	2.00	418.63	Max
20	0.90	286.54	Min
21	0.60	359.20	Max
22	1.30	443.75	Max
23	0.60	430.25	Max
24	1.40	427.90	Max
25	0.65	203.73	Min
26	2.50	317.14	Max
27	1.05	227.17	Min
28	1.30	250.90	Min
29	1.30	322.75	Max
30	2.20	326.48	Max

The complete output of the *What's Best!* solution for the complete LP problem is provided in Appendix C–"Linear Programming Solutions". This optimization problem has taken the software 16 iterations, compared to 1 iteration in the reduced constraint experiment (Table G1). The constraint equations are numbered at 797 with 360 cells to optimize. The value of *Z* in the above solution is 37,045 benefit units, which is considerably lower than the previous two cases. Now the LP is allocating resources to Thrusts with lower benefit values in order to satisfy the added constraints.

Actual 2010-2011 resource assignment

The actual resource assignment for the fiscal year 2010-2011 is presented for FTEs and DRDC Funds by Thrusts in the table below. These data are obtained from CPME. Table G5 contains the allocation of FTEs by DRDC among the 30 Thrusts.

Table G5. Actual FTE resource assignment in fiscal year 2010-2011 (DRDC, 2011b)

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
1	0.00	0.00	0.00	3.28	0.00	0.00	0.00	0.00	0.00	0.00	14.65
2	0.82	0.00	0.00	18.86	0.00	0.00	0.00	0.00	0.00	0.00	0.45
3	0.00	0.00	4.60	0.00	0.00	0.00	0.00	23.12	1.40	0.20	0.00
4	0.50	0.05	6.60	1.20	0.20	0.00	4.55	0.00	10.95	0.20	0.00
5	7.55	0.00	0.10	3.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	1.45	0.40	21.16	2.95	5.25	1.75	0.00	0.00	9.10	13.66	0.00
7	0.65	0.00	0.50	5.40	0.00	27.09	0.11	0.00	8.55	0.00	0.00
8	9.00	0.00	5.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.35	7.45	0.00	0.00	1.82	0.00	0.00	0.00	0.00
10	2.65	5.85	0.00	1.65	0.00	0.00	0.00	0.50	0.00	1.28	1.90
11	3.20	11.45	6.85	0.40	1.30	0.00	0.65	0.00	0.00	0.00	0.00
12	0.00	0.00	0.75	0.20	0.55	0.25	5.95	6.43	1.40	0.95	0.00
13	1.45	5.35	1.58	0.45	0.00	0.20	9.99	14.58	19.06	2.15	0.28
14	0.30	0.00	0.00	0.10	2.55	4.50	8.70	0.90	6.45	0.00	0.00
15	0.00	0.00	0.00	9.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	12.30	0.25	0.00	0.00	0.60	0.10	0.00	0.00	0.00
17	0.30	0.00	2.62	0.00	0.55	0.00	8.90	0.85	14.25	0.00	0.00
18	0.00	0.00	0.00	6.50	0.80	0.00	0.00	0.00	0.20	0.40	0.00
19	0.00	0.00	0.00	0.00	0.00	0.85	0.00	0.00	0.00	3.38	0.00
20	4.80	0.70	0.10	0.20	0.00	0.00	0.10	0.00	0.00	1.35	0.00
21	0.00	0.00	0.00	6.70	0.00	0.00	0.00	0.00	0.00	2.45	0.90
22	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.50	24.07
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.70
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.25	15.40
25	1.00	0.00	0.00	0.95	0.00	0.00	0.00	0.65	0.00	14.41	2.00
26	0.00	0.00	0.00	0.00	0.10	0.00	0.00	27.61	0.00	1.10	0.00
27	6.70	0.00	0.05	2.70	0.00	0.00	0.00	0.00	0.00	0.55	3.20
28	2.30	21.19	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	0.00	2.25	14.10	0.00	0.05	0.00	0.30	0.00	1.90	0.80	1.70
30	4.75	9.30	18.31	3.50	0.60	0.15	1.85	0.00	0.00	0.00	0.00

Table G6 contains the actual DRDC fund allocation among the Thrusts.

Table G6. Actual DRDC fund allocation for fiscal year 2010-2011 (Source: DRDC, 2011b)

Thrusts	Y_i (M$)
1	0.800
2	1.300
3	1.850
4	1.295
5	1.095
6	1.860
7	1.255
8	1.275
9	0.325
10	0.900
11	0.325
12	0.910
13	2.481
14	1.036
15	0.514
16	1.255
17	1.060
18	0.995
19	1.410
20	1.175
21	0.295
22	0.935
23	0.270
24	0.980
25	0.875
26	1.759
27	1.415
28	1.705
29	0.850
30	1.634

LP Sensitivity Analysis

In the DRDC problem the coefficients which are included in the benefit function were estimated based on the resource assignment of previous years since these coefficients are in fact not directly determinable from the actual process. Therefore, it is imperative to know how changes in the coefficients can affect the output of the algorithm. Through sensitivity analysis, robustness of the current solution (Table G3 and Table G4) can be investigated. Sensitivity analysis determines the range of variation of the coefficients for which the characteristics of the current solution remain optimal.

Structural changes are not considered part of the sensitivity analysis (i.e. addition/deletion of a variable or a constraint). Through sensitivity analysis, changes in the following coefficients are investigated:

- Coefficients of the objective function (function Z in section 3.3 LP Formulation)
- The right-hand side (RHS) of the constraint equations (all constraints are listed in section 3.3 LP Formulation)

The coefficients of the objective function correspond to the value of resources in the DRDC problem, which is equivalent to the benefit function in this case. The right hand-side of the constraint equations in DRDC problem is related to the availability of FTEs in various aspects (Total FTEs available, total allowable FTEs for each Thrust, Total FTEs available within each skill type, etc). Coefficients in the constraint equations provide insight into the relationship between variables of the LP process from various angles. The focus is on coefficients that entail some degree of uncertainty.

LP Elements for Sensitivity Analysis

RHS of constraints:

Constraints with respect to the FTEs are reliable data. They refer to the quantities of total FTEs available, FTEs of certain types available and quantities of multi-tasking FTEs. The second set of constraints involves the maximum and minimum allowable FTE assignment to each Thrust. These values are extracted from previous years' data and are not strictly determined in the process, but rather are implicitly accounted for in subsequent allocation years.

Coefficients of the objective function:

The most uncertain portion of the deterministic LP model is the benefit function which is designed proportional to various indecisive factors including the weights of the scores of criteria and resource assignment of the preceding year. This accounts for 360 coefficients.

The LP model allocates the minimum amount of required resources to all Thrusts and then redistributes the remaining to the Thrusts with higher weights. Therefore inspecting the LP solution of Table G4, it is observed that all Thrusts have either received what they were asking for (the maximum amount) or are assigned the minimum amount. There is only one Thrust (Thrust 1) that optimally receives an intermediary amount somewhere between the minimum and the maximum. Increases in the values of coefficients do not affect the values of the variables until the point where a Thrust with lower weight (minimum limits) joins the upper weight class (maximum limits).

Sensitivity of LP Results

What's Best! includes tools to provide valuable sensitivity information. One of the tools provided which is termed 'Dual Value' computes the rate of improvement when the RHS of a constraint is increased. The following groups for FTE type maximums are defined to correspond to an individual who is capable of being several FTE types (either types 1-3, 4-7, 8-9 or 10-11). This is an interesting constraint since an FTE can be assigned to multiple types in Thrusts and the rate of improvement in the objective function is not dependent to a single Thrust/Type benefit value. The grouped FTE type upper bound constraints are given by:

Group 1: $\sum X_{in} \leq$ FTE_type_Group1_max $(1 \leq n \leq 3)$
Group 2: $\sum X_{in} \leq$ FTE_type_Group2_max $(4 \leq n \leq 7)$
Group 3: $\sum X_{in} \leq$ FTE_type_Group3_max $(8 \leq n \leq 9)$
Group 4: $\sum X_{in} \leq$ FTE_type_Group4_max $(10 \leq n \leq 11)$

The Dual Value sensitivity analysis tool for these constraints are presented in Table G7.

Table G7. Dual values for RHS of FTE type for groups constraints

Groups	**$\sum X_{nj}$**	**FTE_type_Group_max**	**Dual Value**
1	188	188	2.59
2	179	179	2.68
3	142	142	5.89
4	131	131	0

The sensitivity results of Table G7 indicate that increasing the quantity of FTE of Group 3 (capable of being types 8 or 9) will produce the highest per unit benefit increase to our objective function per unit increase in the FTE type maximum. Whereas, for an FTE belonging to Group 4 (types 10 or 11), an increase in the FTE type group maximum would have no effect on the current optimal solution. As mentioned, the dual value displays the rate of change in the value of objective function with a unit increase in the RHS in the pertinent constraint. As determined in the report, the Dual Values for the RHS of the FTE group maximum can increase up to an additional 2.59 with addition of each FTE units of Group 1 (types 1, 2 or 3).

Another set of constraints that are analyzed are the maximum values set for the DRDC fund allocation. Performing the dual value analysis for these constraints, the Thrusts in Table G8 all demonstrated gains in the objective value per unit increase in these allocations limits by Thrust.

Table G8. Dual values for the RHS of maximum fund constraints for Thrusts

Thrust	Dual Value	Thrust	Dual Value
6	27.19	19	117.51
7	4.93	21	58.09
12	2.81	22	142.64
14	3.97	23	129.14
15	65.64	24	126.79
16	15.63	26	16.03
17	61.34	29	21.64
18	100.39	30	25.37

For example, relaxing the RHS in the constraint for Thrust 22 by increasing the allocation maximum is deemed the most beneficial to our objective function with a unit benefit increase of 142.64 per unit increase in the allocation maximums. All the remaining Thrusts except Thrust 1 (which is awarded a fund between its minimum and maximum bounds) have their dual value determined to be non-zero as in Table G8.

Table G9 contains the dual values for the minimum DRDC fund allocation. Thrust 5 has the highest Dual Value (109.11), implying that decreasing the minimum constraint will improve the objective function by the largest amount per unit increase in the minimum fund constraint, while decreasing the minimum for Thrust 13 provides the lowest per unit additional benefit.

Table G9. Dual values for the RHS of minimum fund constraints for Thrusts

Thrust	Dual Value	Thrust	Dual Value
2	8.15	11	9.25
3	23.15	13	5.35
4	46.81	20	14.57
5	109.11	25	97.38
8	24.87	27	76.94
9	103.11	28	50.21
10	70.02		

The same concept can be applied to the minimum and maximum constraints set for each FTE type for Thrusts which is an 11×30 matrix. Some of the dual values of these two sets of constraints are inevitability zero as the solutions are smaller than the RHS values. Appendix F–"LP Sensitivity Analysis for FTE Types" contains the matrices for the dual values of maximum and minimum FTE constraints. They suggest that increasing the maximum allowed FTE would only result in a handful of Thrusts contributing to gain in objective function. However, increasing the minimum quantity required for each Thrusts results in reduction in the value of the objective function for many Thrusts. The latter is due to the fact that by increasing the minimum value, the LP solver is dictated to allocate FTEs to Thrusts that do not necessarily contribute more benefit.

Appendix H – AHP Data Grids

This section contains the data grid as entered into Expert Choice and pairwise comparisons data. The values in data grid are extracted from CPME and are the average of values for projects within each Thrust.

	Distributive	INCR	INCR	INCR
AID	Alternative	Design Scope (L: 0.000 G: 0.000)	Design Hard Problems (L: 0.000 G: 0.000)	Design Originality (L: 0.000 G: 0.000)
A1	1	3.78	4.44	3.78
A2	2	3.73	4	3.93
A3	3	3.83	4	3.75
A4	4	3.6	3.9	3.4
A5	5	3.43	3.29	3.43
A6	6	3.38	3.63	3.63
A7	7	3.7	2.6	3.2
A8	8	3.83	3.33	3.83
A9	9	3.67	4.67	3
A10	10	4.71	3.43	4.14
A11	11	4.14	3.86	4
A12	12	4	3.78	3.56
A13	13	3.94	4.11	3.89
A14	14	3.71	3.78	3.89
A15	15	3.75	3.75	3.5
A16	16	3.6	4	4
A17	17	3.8	3.91	3.73
A18	18	4.33	3	3.67
A19	19	4.13	3.13	3.38
A20	20	3.29	3.25	3.5
A21	21	4	4	3
A22	22	3.88	4.5	3.88
A23	23	3.75	3.5	3.25
A24	24	3	2.9	3.5
A25	25	2.83	3	3.1
A26	26	4.07	3.86	3.64
A27	27	3.63	4	3.88
A28	28	2.57	4.43	4.14
A29	29	4.5	3.5	3.75
A30	30	3.91	3.82	4

Figure H1. Partial data grid in Expert Choice showing Scope, Hard Problems and Originality

	Distributive	INCR	INCR	INCR
AID	Alternative	Accountability Leverage (L: 0.000 G: 0.000)	Accountability Schedule Management (L: 0.000 G: 0.000)	Accountability Budget Management (L: 0.000 G: 0.000)
A1	1	3.44	3	5
A2	2	2.8	3.07	4.07
A3	3	3.33	3.83	4.58
A4	4	3.3	4.2	5
A5	5	2.14	3.29	4.86
A6	6	3.69	3.19	4.63
A7	7	3.2	3	4.8
A8	8	2	4.5	5
A9	9	1.33	3.67	5
A10	10	2.71	4.57	4.71
A11	11	3.57	4.14	5
A12	12	2	4.11	4.86
A13	13	4.33	4.22	4.39
A14	14	3.11	3.56	4.89
A15	15	2.75	4.25	5
A16	16	3.4	3.7	4.8
A17	17	4.45	3.91	4.82
A18	18	3.5	3.83	4.17
A19	19	4	4.38	5
A20	20	3.13	3.5	4.25
A21	21	3.6	3.6	5
A22	22	3.38	4	4.88
A23	23	3.25	4	5
A24	24	3.7	4.2	5
A25	25	2.3	4.4	5
A26	26	3.86	4.57	4.71
A27	27	2.63	3.25	4.63
A28	28	2.57	4	5
A29	29	4.13	2.88	4.88
A30	30	4.09	3.45	4.45

Figure H2. Partial data grid in Expert Choice showing Leverage, Schedule management and Budget management.

	Distributive	INCR	INCR	INCR
AID	**Alternative**	Outcome Exploitation Plan (L: 0.000 G: 0.000)	Outcome Potential for Uptake (L: 0.000 G: 0.000)	Overall Quality (L: 0.000 G: 0.000)
A1	1	0.33	3.33	3.67
A2	2	0.41	3.53	3.73
A3	3	0.29	3.17	3.25
A4	4	0.17	3.1	3
A5	5	0	3	2.86
A6	6	0.47	3.94	3.25
A7	7	0.45	3.8	2.8
A8	8	0.43	2.67	3.17
A9	9	0	4.67	3.33
A10	10	0.11	3.29	2.71
A11	11	0.31	3.43	2.57
A12	12	0.54	3.89	2.67
A13	13	0.26	3.39	3.28
A14	14	0.45	3.11	2.56
A15	15	0.75	3.75	3.5
A16	16	0.45	3.4	2.9
A17	17	0.55	3.73	3.55
A18	18	1	2.67	2.5
A19	19	1	2.5	2.38
A20	20	0.44	2.38	3
A21	21	0.67	3.6	2.8
A22	22	1	4.5	4.13
A23	23	1	4.25	3.75
A24	24	1	3.6	3
A25	25	0.09	2.1	3
A26	26	0.47	2.43	3.21
A27	27	0.11	2.75	3.38
A28	28	0.22	2.43	3.14
A29	29	0.46	2.5	3
A30	30	0.43	3.55	3.45

Figure H3. Partial data grid in Expert Choice showing Exploitation plan, Potential for uptake and Overall quality.

The following pages include the tables collected from participant containing the pairwise comparisons between criteria. The Consistency Ratio (*CR*) or inconsistency as displayed here is calculated by *Expert Choice* upon entering these values in the software.

Pair-wise comparison by Participant 1:

Table H1. Pairwise comparison with respect to the Main Objective

Main Objective	Design	Accountability	Outcome	Overall Quality
Design		5	-2	-2
Accountability			-5	-5
Outcome				2
Overall Quality				

Inconsistency: 0.05

Table H2. Pairwise comparison with respect to Design

Design	Scope	Hard Problems	Originality
Scope		3	1
Hard Problems			2
Originality			

Inconsistency: 0.35

Table H3. Pairwise comparison with respect to Accountability

Accountability	Leverage	Schedule Management	Budget Management
Leverage		6	8
Schedule Management			4
Budget Management			

Inconsistency: 0.13

Table H4. Pairwise comparison with respect to Outcome

Outcome	Exploitation Plan	Potential for Uptake
Exploitation Plan		-5
Potential for Uptake		

Inconsistency: 0.00

Pair-wise comparison by Participant 2:

Table H5. Pairwise comparison with respect to the Main Objective

Main Objective	Design	Accountability	Outcome	Overall Quality
Design		1	1	-4
Accountability			-2	1
Outcome				-4
Overall Quality				

Inconsistency: 0.17

Table H6. Pairwise comparison with respect to Design

Design	Scope	Hard Problems	Originality
Scope		-7	-3
Hard Problems			7
Originality			

Inconsistency: 0.13

Table H7. Pairwise comparison with respect to Accountability

Accountability	Leverage	Schedule Management	Budget Management
Leverage		2	-5
Schedule Management			-6
Budget Management			

Inconsistency: 0.03

Table H8. Pairwise comparison with respect to Outcome

Outcome	Exploitation Plan	Potential for Uptake
Exploitation Plan		1
Potential for Uptake		

Inconsistency: 0.00

Pair-wise comparison by Participant 3:

Table H9. Pairwise comparison with respect to the Main Objective

Main Objective	Design	Accountability	Outcome	Overall Quality
Design		-3	-7	-5
Accountability			-5	-3
Outcome				3
Overall Quality				

Inconsistency: 0.04

Table H10. Pairwise comparison with respect to Design

Project Design	Scope	Hard Problems	Originality
Scope		-5	3
Hard Problems			5
Originality			

Inconsistency: 0.13

Table H11. Pairwise comparison with respect to Accountability

Accountability	Leverage	Schedule Management	Budget Management
Leverage		3	-3
Schedule Management			-5
Budget Management			

Inconsistency: 0.04

Table H12. Pairwise comparison with respect to Outcome

Outcome	Exploitation Plan	Potential for Uptake
Exploitation Plan		5
Potential for Uptake		

Inconsistency: 0.00

Appendix I – AHP Alternative Ranking

Results of the phase I of the AHP methodology for the 5 groups of Thrusts are displayed in the following pages. The values are extracted from Expert Choice.

Table I1. Phase I AHP ranking results

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
High DND fund	**High DRDC fund**	**Low quantity of scientists**	**Low DND fund**	**Midrange DND and DRDC fund**
Thrust (Rank)	Thrust (Rank)	Thrust (Rank)	Thrust (Rank)	Thrust (Rank)
17 (0.200) 6 (0.183) 13 (0.164) 7 (0.161) 20 (0.148) 4 (0.143)	30 (0.196) 19 (0.189) 26 (0.172) 3 (0.171) 28 (0.150) 25 (0.121)	23 (0.259) 15 (0.228) 16 (0.186) 18 (0.185) 5 (0.141)	24 (0.206) 21 (0.180) 1 (0.178) 8 (0.154) 9 (0.154) 10 (0.128)	22 (0.214) 2 (0.151) 12 (0.139) 29 (0.130) 14 (0.125) 11 (0.123) 27 (0.118)

Results of the phase II of AHP methodology for all Thrusts. The values are extracted from Expert Choice.

Table I2. Phase II AHP ranking results

Phase II Thrust Groups	Thrusts	Priority
Group 1 - Ranked First	17, 30, 23, 24, 22	0.215
Group 2 - Ranked Second	6, 19, 15, 21, 2	0.184
Group 3 - Ranked Third	13, 26, 16, 1, 12	0.167
Group 4 - Ranked Fourth	7, 3, 18, 8, 9, 29	0.160
Group 5 - Ranked Fifth	20, 28, 5, 14	0.138
Group 6 - Ranked Sixth	4, 25, 10, 11, 27	0.135

Appendix J – 'R' Data Components for Clustering

The following pieces of code written in 'R' apply k-means algorithm and graph DBI, cluster-compactness and between cluster separation.

Following are the Thrusts' variables used for clustering as entered into R's command prompt:

```
Thrusts_info=c(375000,10000,23,2123263,22.75,875000,362000,17,154
6640,16.99,1543000,1125900,42,3657537,22.84,1026000,6122000,25,22
20132,17.45,1215000,366600,13,1155142,7.95,1578000,6374600,56,479
6937,24.25,1115000,3597090,51,4239183,25.26,880000,270000,15,1360
074,11.53,320000,0,10,840617,10,623000,205500,18,1563968,15.20,58
0000,749000,31,2852921,18.90,811000,2101350,25,2137862,13.34,2005
000,5573200,69,5602976,35.31,1025000,2074985,26,2296459,15.31,620
000,925000,10,905251,9.36,1018000,1004700,14,1343126,6.8,725000,6
350220,38,3332905,18.30,305000,80000,8,702840,5.95,1360000,128040
0,10,857537,2.93,1155000,2853000,10,850396,7.7,350000,0,17,146714
2,16.52,450000,455000,23,2014530,21.88,332000,200000,10,757403,9.
23,1013000,50000,21,1741114,15.52,1386000,135000,15,1272032,9.05,
2107000,167000,46,3661503,19.41,929500,658000,16,1458562,11.85,14
05000,150000,24,2131874,19.21,1109000,1943000,34,3019920,26.70,14
39000,1510000,41,3672196,27.08)
```

The following command structures the above data into a matrix of 30 rows and 5 columns:

```
Thrusts=matrix(Thrusts_info,ncol=5,byrow=T)
```

The following code implements the Davies–Bouldin Index (DBI):

```
Davies.Bouldin.Index = function(CC,WSS,ClusterSize){

# The following code for DBI function is a personal #
# communication and was used with the author's consent #

# CC- Center of cluster
# WSS - Within sum of squares
# ClusterSize - Size of the cluster

N = nrow(CC)                      # Number of clusters
S = sqrt(WSS/ClusterSize)   # inter cluster distance
M = as.matrix(dist(CC))     # get the dist between centers

# Get the ratio between intercluster/centre.dist
```

```
Ratio = matrix(0,N,N)
for(i in 1:(N-1))
{
 for(j in (i+1):N)
 {
     Ratio[i,j] = (S[i]+S[j])/M[i,j]
     Ratio[j,i] = Ratio[i,j]
  }
 }
return(mean(apply(Ratio,1,max)))
}
```

The following code conducts 10 runs of k-means with random initial conditions for cluster sizes from 2 to 14. It graphs the plots of DBI along, cluster-compactness and between cluster separations. Plots are shown on the following pages.

```
Cluster.Thrusts.kmeans=function(){

errs <- matrix(0,10,13)
DBI <- matrix(0,10,13)
separation <- matrix(0,10,13)
errs_sum <- rep(0,13)
DBI_sum <- rep(0,13)
separation_sum <- rep(0,13)
errs_ave <- rep(0,13)
DBI_ave <- rep(0,13)
separation_ave <- rep(0,13)

   #
for(j in 1:10){
  for (i in 2:14) {
   KM <- kmeans(thrusts, i, 10000)
   errs[j,i-1] <- KM$tot.withinss
   DBI[j,i-1] <- Davies.Bouldin.Index(KM$centers, KM$withinss, 
KM$size)
   separation[j,i-1] <- KM$betweenss/KM$totss
  }
   #
}
# Computing the average over 10 runs
for(j in 1:10){
  for (i in 2:14) {
     errs_sum[i-1] <- errs_sum[i-1]+ errs[j,i-1]
     DBI_sum[i-1] <- DBI_sum[i-1]+ DBI[j,i-1]
     separation_sum[i-1] <- separation_sum[i-1]+ separation[j,i-
1]
     }
     }
# Divide by 10
errs_ave <- errs_sum/10
```

```
DBI_ave <- DBI_sum/10
separation_ave <- separation_sum/10


par(mfrow=c(3,1))
plot(2:14, errs_ave, main = paste("Total Whitin SS"),xlab="Number
of centers")
lines(2:14, errs_ave)

plot(2:14, DBI_ave, main = paste("Davies-Bouldin
Index"),xlab="Number of centers")
lines(2:14, DBI_ave)

plot(2:14, separation_ave, main =
paste("Separation"),xlab="Number of centers")
lines(2:14, separation_ave)
}
```

Output of the above program is the average over 10 iterations:

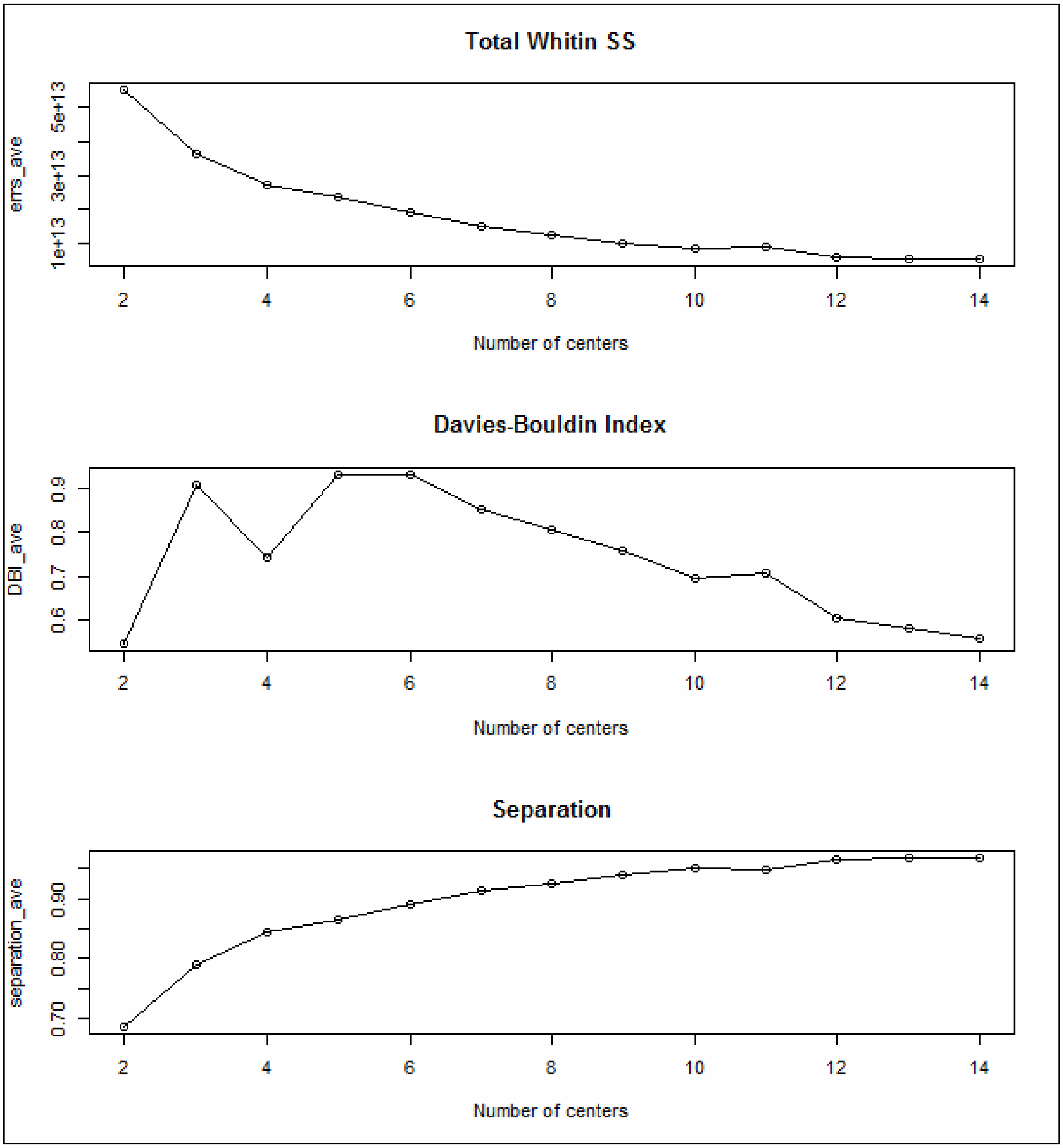


Figure J1. Average values of Total-within-sum-of-squares, DBI and Separation over 10 k-means iteration for cluster sizes between 2 and 14 for DRDC Thrust clustering

The following code runs the k-means algorithm for 5 clusters and 10,000 iterations. Our data is stored in a matrix called `Thrusts`. Following is the output of the above command. Size of the clusters, their means for each variable, clustering vector (cluster label for each Thrust), within cluster sum of squares and degree of separation are presented.

```
R> KM <-kmeans(Thrusts, 5, 10000)

R> KM
K-means clustering with 5 clusters of sizes 11, 5, 6, 5, 3

Cluster means:
       [,1]      [,2]     [,3]    [,4]     [,5]
1  629818.2  162045.5 16.90909 1477224 14.98000
2 1355600.0 1098980.0 38.80000 3372815 22.98600
3 1088083.3  728283.3 13.00000 1165275  7.99000
4 1289800.0 5603422.0 47.80000 4038427 24.11400
5  997000.0 2343111.7 20.33333 1761572 12.11667

Clustering vector:
 [1] 1 1 2 4 3 4 4 1 1 1 2 5 4 5 3 3 4 1 3 5 1 1 1 1 3 2 3 1 2 2

Within cluster sum of squares by cluster:
[1] 4.325614e+12 3.791009e+12 1.627102e+12 1.332875e+13
1.708611e+12
 (between_SS / total_SS =  85.8 %)
```

Following commands obtains the total within sum of squares, DBI and Separation of the above clustering results.

```
R> KM$tot.withinss
[1] 2.478109e+13

R> Davies.Bouldin.Index(KM$centers, KM$withinss, KM$size)
[1] 1.013694

R> KM$betweenss/KM$totss
[1] 0.8577414
```

The following lines are executed in `R` and resulting in the following Q-Q plots:

```
R> qqnorm(Thrusts[,1]);qqline(Thrusts[,1], col = 2)
R> qqnorm(Thrusts[,2]);qqline(Thrusts[,2], col = 2)
R> qqnorm(Thrusts[,3]);qqline(Thrusts[,3], col = 2)
R> qqnorm(Thrusts[,4]);qqline(Thrusts[,4], col = 2)
R> qqnorm(Thrusts[,5]);qqline(Thrusts[,5], col = 2)
```

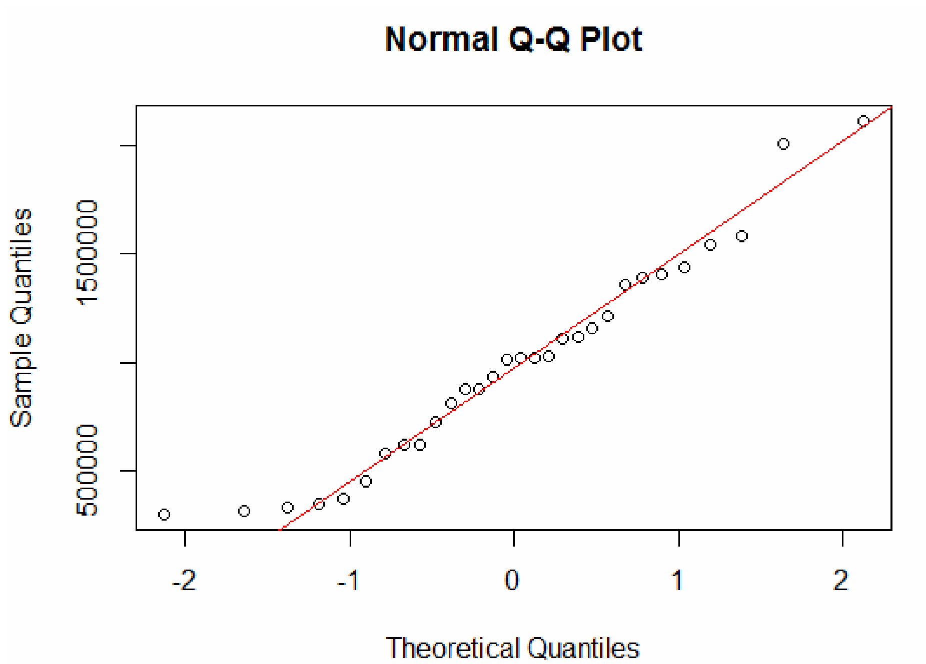


Figure J2. Q-Q plot for DRDC Fund

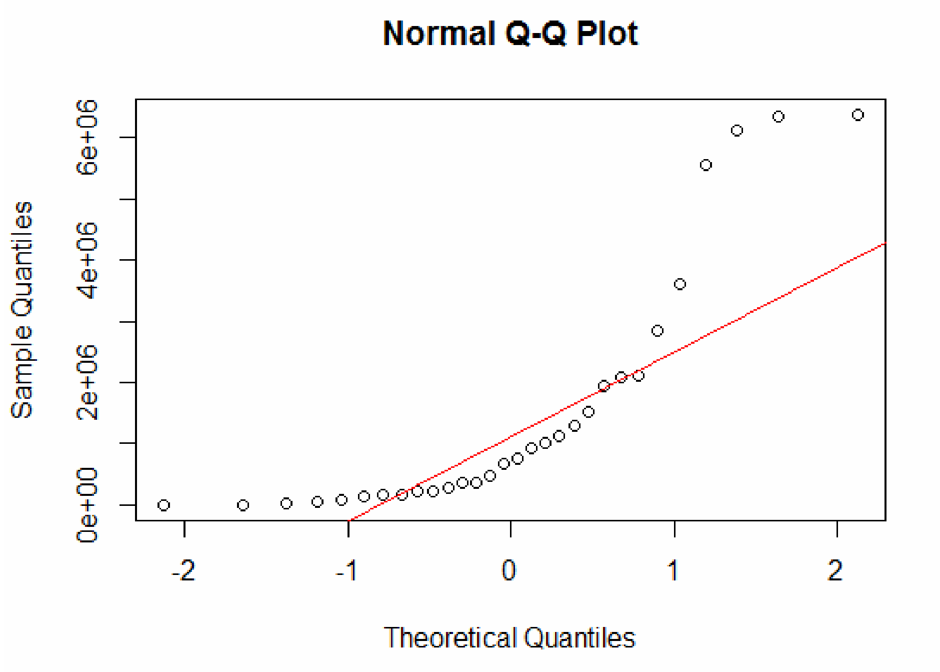


Figure J3. Q-Q plot for DND Leveraging

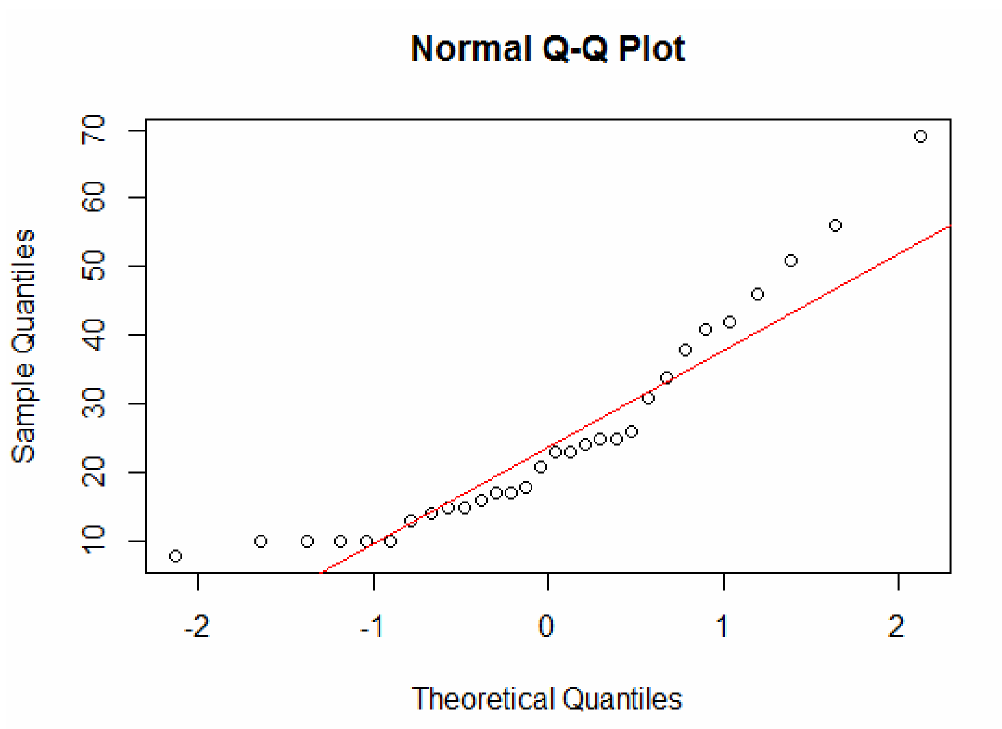


Figure J4. Q-Q plot for Total FTEs

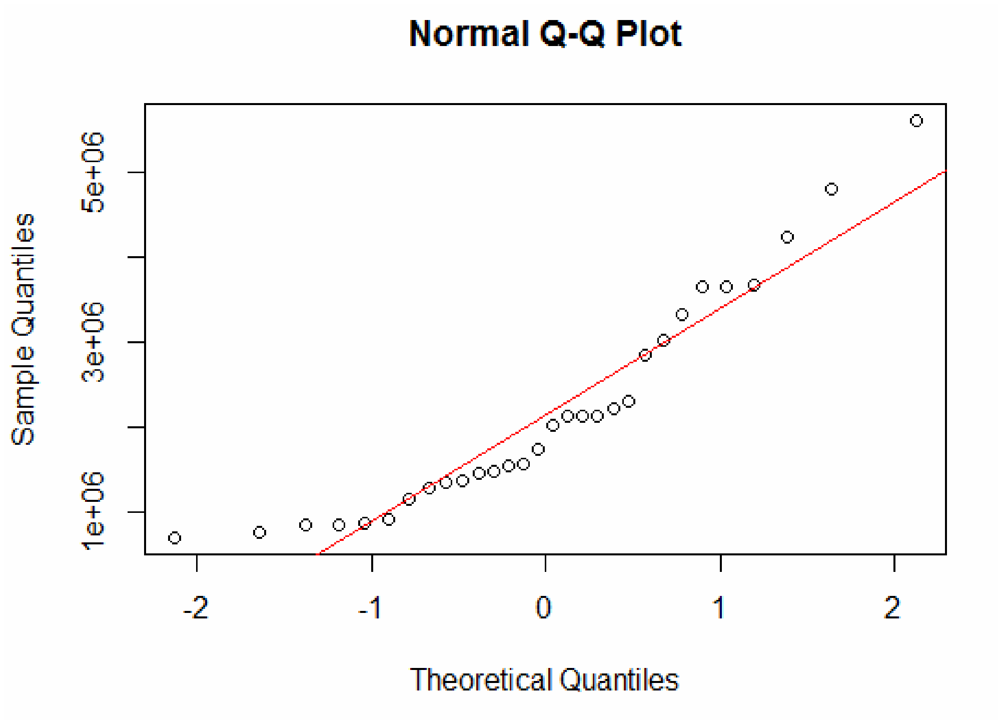


Figure J5. Q-Q plot for Total FTEs Budget

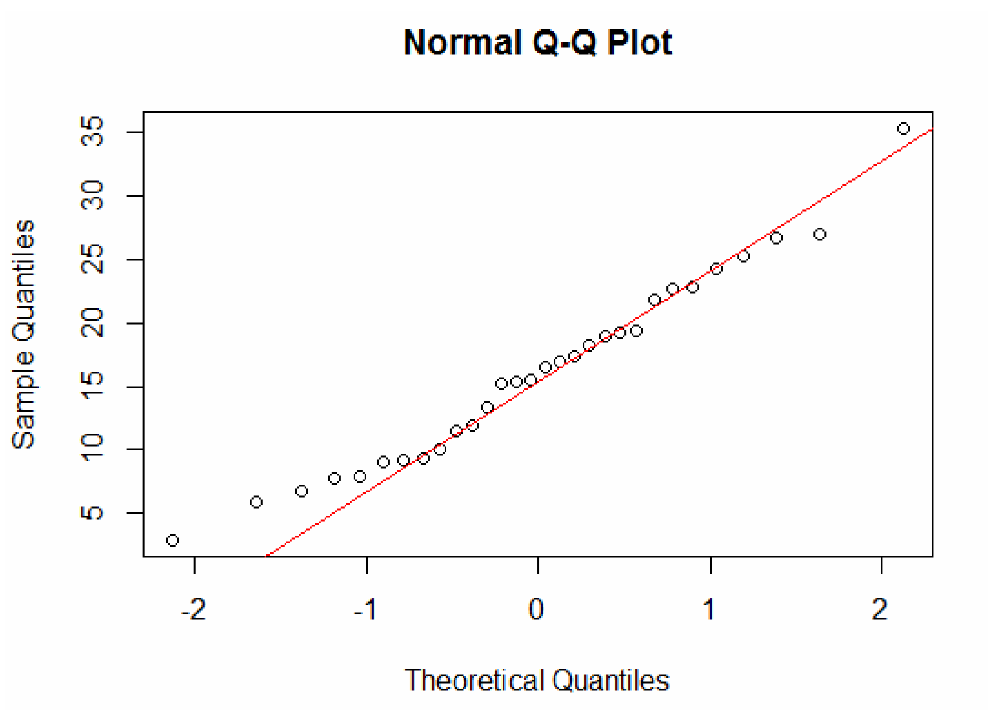


Figure J6. Q-Q plot for number of Scientists

The point pattern in the above Q-Q plots for DND Leveraging, Total FTEs and FTEs Budget are not linear. Therefore the above-mentioned criteria are not normally distributed.

The following page displays the histograms for the five criteria. The graphs for DND Leveraging, Total FTEs and FTEs Budget are skewed, resulting in conclusion that they are not normally distributed.

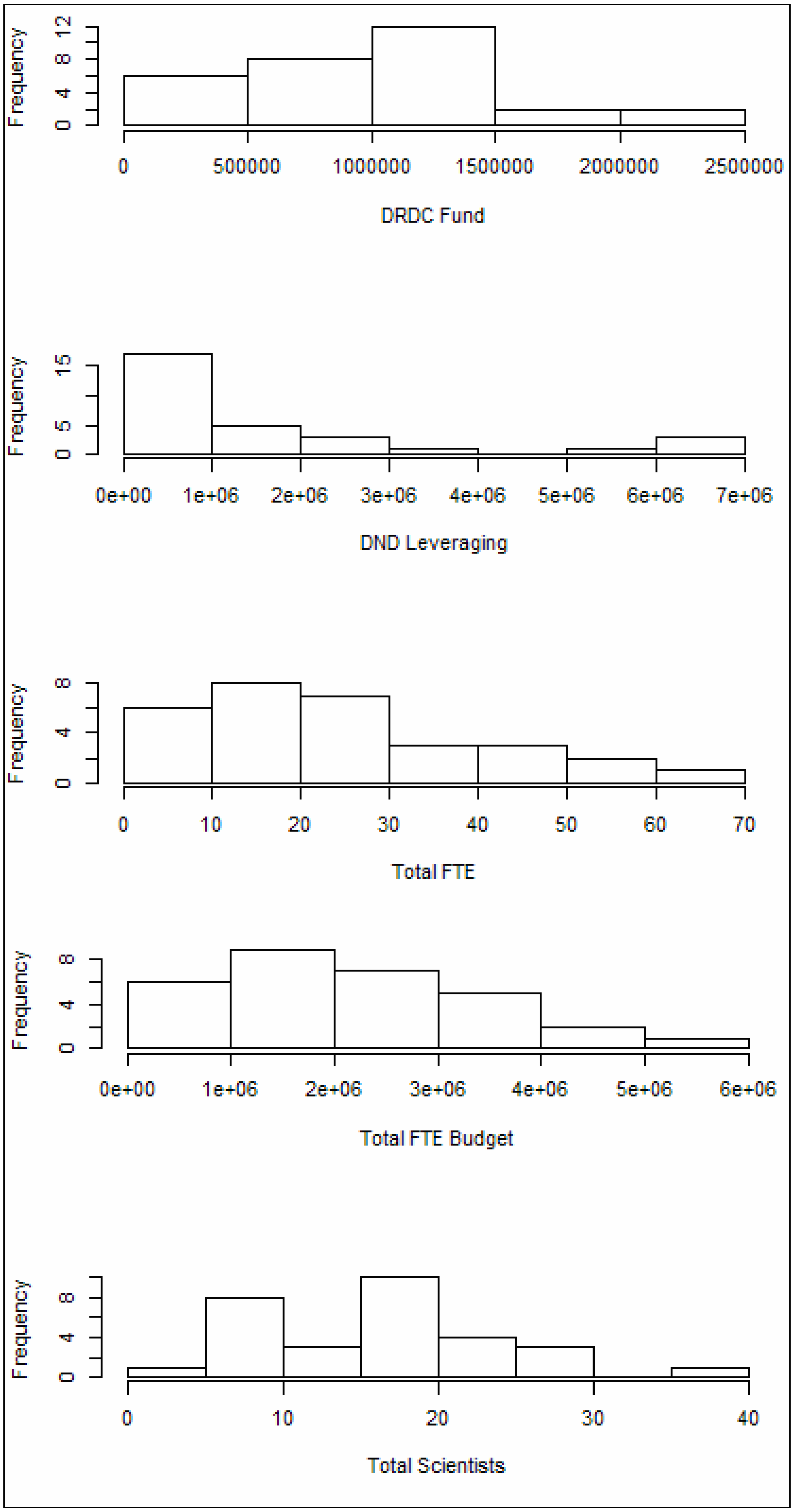


Figure J7. Histograms of distribution of Thrust variables

Appendix K – Fitness calculations for manual clustering

The following are the codes from 'R' to compute the DBI, total-within-cluster-sum-of-squares and also separation (ratio of *between-cluster-sum-of-squares* to *total-within-cluster-sum-of-squares*) for the manual clustering of Thrusts. Matrix `Thrusts` was defined previously.

```
within.css=function(){

#Adding Thrust numbers to each row
row_num <-
(1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,2
5,26,27,28,29,30)
row_col <- matrix(row_num,ncol=1,byrow=T)
Thrusts_c <- cbind(Thrusts,row_col)


# Adding Thrusts numbers in a column

cluster1 <-
cbind(Thrusts_c[4,],Thrusts_c[6,],Thrusts_c[7,],Thrusts_c[13,],Th
rusts_c[17,],Thrusts_c[20,])
cluster1 <- t(cluster1)

cluster2 <-
cbind(Thrusts_c[3,],Thrusts_c[19,],Thrusts_c[25,],Thrusts_c[26,],
Thrusts_c[28,],Thrusts_c[30,])
cluster2 <- t(cluster2)

cluster3 <-
cbind(Thrusts_c[5,],Thrusts_c[15,],Thrusts_c[16,],Thrusts_c[18,],
Thrusts_c[23,])
cluster3 <- t(cluster3)

cluster4 <-
cbind(Thrusts_c[1,],Thrusts_c[8,],Thrusts_c[9,],Thrusts_c[10,],Th
rusts_c[21,],Thrusts_c[24,])
cluster4 <- t(cluster4)

cluster5 <-
cbind(Thrusts_c[2,],Thrusts_c[11,],Thrusts_c[12,],Thrusts_c[14,],
Thrusts_c[22,],Thrusts_c[27,],Thrusts_c[29,])
cluster5 <- t(cluster5)

#Calculating the mean of each column
mean1 <-
cbind(mean(cluster1[,1]),mean(cluster1[,2]),mean(cluster1[,3]),me
an(cluster1[,4]),mean(cluster1[,5]))
```

```
mean2 <-
cbind(mean(cluster2[,1]),mean(cluster2[,2]),mean(cluster2[,3]),me
an(cluster2[,4]),mean(cluster2[,5]))
mean3 <-
cbind(mean(cluster3[,1]),mean(cluster3[,2]),mean(cluster3[,3]),me
an(cluster3[,4]),mean(cluster3[,5]))
mean4 <-
cbind(mean(cluster4[,1]),mean(cluster4[,2]),mean(cluster4[,3]),me
an(cluster4[,4]),mean(cluster4[,5]))
mean5 <-
cbind(mean(cluster5[,1]),mean(cluster5[,2]),mean(cluster5[,3]),me
an(cluster5[,4]),mean(cluster5[,5]))
meanALL <- cbind(mean1[1,], mean2[1,], mean3[1,], mean4[1,],
mean5[1,])
meanALL <- t(meanALL)


#Computing the total within sum of squares for Cluster 1
WCSS1<- rep(0, 5)

  for (i in 1:5)
  {
     for(j in 1:6)
     {
          WCSS1[i] = WCSS1[i] + (cluster1[j,i]-
mean1[i])*(cluster1[j,i]-mean1[i])
     }
  }

#Computing the total within sum of squares for Cluster 2
WCSS2<- rep(0, 5)

  for (i in 1:5)
  {
     for(j in 1:6)
     {
          WCSS2[i] = WCSS2[i] + (cluster2[j,i]-
mean2[i])*(cluster2[j,i]-mean2[i])
     }
  }

#Computing the total within sum of squares for Cluster 3
WCSS3<- rep(0, 5)

  for (i in 1:5)
  {
     for(j in 1:5)
     {
          WCSS3[i] = WCSS3[i] + (cluster3[j,i]-
mean3[i])*(cluster3[j,i]-mean3[i])
     }
  }
```

```
#Computing the total within sum of squares for Cluster 4
WCSS4<- rep(0, 5)

  for (i in 1:5)
  {
     for(j in 1:6)
     {
          WCSS4[i] = WCSS4[i] + (cluster4[j,i]-
mean4[i])*(cluster4[j,i]-mean4[i])
     }
  }

#Computing the total within sum of squares for Cluster 5
WCSS5<- rep(0, 5)

  for (i in 1:5)
  {
     for(j in 1:7)
     {
          WCSS5[i] = WCSS5[i] + (cluster5[j,i]-
mean5[i])*(cluster5[j,i]-mean5[i])
     }
  }

WCSSALL <- cbind(WCSS1[], WCSS2[], WCSS3[], WCSS4[], WCSS5[])
WCSSALL <- t(WCSSALL)
print(paste("Total within cluster sum of squares:"))
print(sum(WCSSALL))

#Entering cluster sizes
ClusterSize <- c(6, 6, 5, 6, 7)

#Calling DBI function
DBIC <- Davies.Bouldin.Index(meanALL , WCSSALL , ClusterSize )
print(paste("DBI:"))
print(DBIC)

#Calculating total sum of squares (TSS)
TSS <- 0
overall.mean <- mean(Thrusts)

  for (i in 1:5)
  {
     for(j in 1:30)
     {
          TSS = TSS + (Thrusts[j,i]-overall.mean)*(Thrusts[j,i]-
overall.mean)
     }
  }
```

```
sep2 <- ((TSS-sum(WCSSALL))/TSS)
print(paste("Separation:"))
print(sep2)
}
```

Appendix L – Questionnaire for AHP pairwise comparison

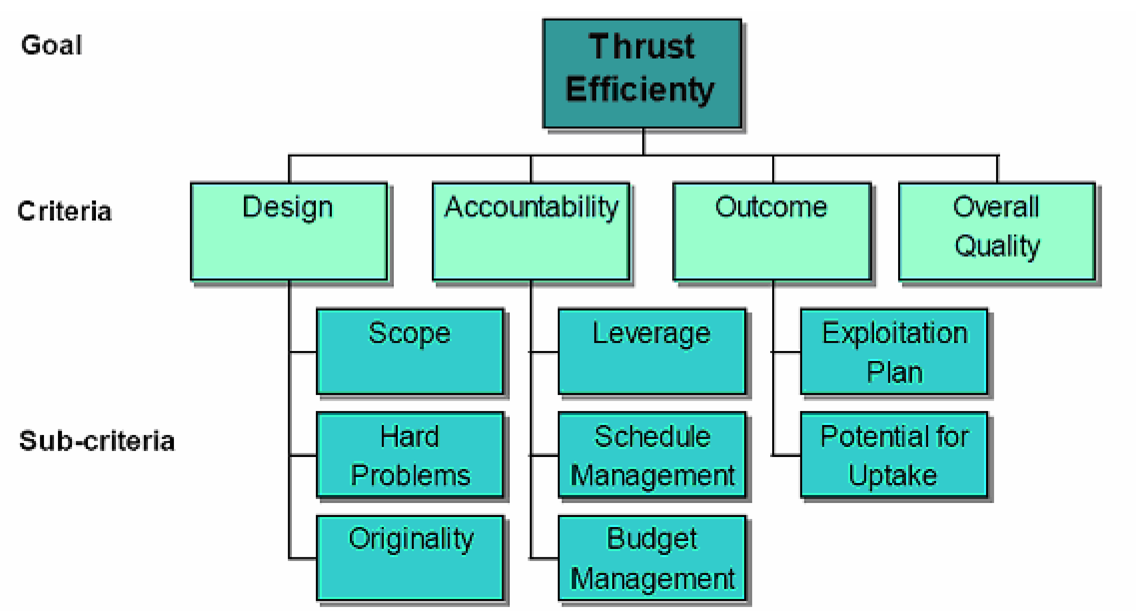
Following is the content of the questionnaire that was sent out to participants in the pair-wise comparison process.

Strategic Program Prioritization at DRDC
Pair-wise comparison of Thrusts' evaluation criteria

Participant's Name:

The objective of this exercise is to rank criteria which are used to evaluate project groups (Thrusts). In order to rank Thrusts, the criteria are structured in a hierarchy of 3 levels. Graph below displays the structure of the hierarchy.

1- On the top level is the main objective which is the Thrust Efficiency.
2- The second level includes the main criteria.
3- The third level contains the sub-criteria.



In order to determine the importance/weight of each criterion, pair-wise comparisons between the elements are performed. Please read the instructions on the next page and fill out the tables for the following items on the following pages: Main Objective, Design Criteria, Accountability Criteria, and Outcome Criteria.

Instructions are provided on the next sheet.

Thank you!

The criteria to be evaluated are placed in a table as shown below. Only the white cells are used for the pair-wise comparison. The grey cells are ignored. Each white cell should contain the level of importance of the criteria in the column to the criteria in the row. Please fill out ALL white cells (total of 13 cells in 4 sheets).

If the criterion in the row is more important, use positive sign (as in Example 2). If the criterion in the column is more important, use negative sign (as in Example 1).

Table 1 summarizes the values used to describe the level of importance. 2, 4, 6 and 8 are the intermediate steps.

Extreme	9	The element in the row is more important
	8	
Very Strong	7	
	6	
Strong	5	
	4	
Moderate	3	
	2	
Equal	1	
	-2	The element in the column is more important
Moderate	-3	
	-4	
Strong	-5	
	-6	
Very Strong	-7	
	-8	
Extreme	-9	

Example 1

If 'Accountability' is "Very Strongly" more important than 'Design', then negative 7 is entered.

Main Objective	Design	Accountability	Outcome	Overall Quality
Design		-7		
Accountability				
Outcome				
Overall Quality				

Example 2
If 'Hard Problems' is "Moderately" more important than 'Originality', then 3 is entered.

Design	Scope	Hard Problems	Originality
Scope			
Hard Problems			3
Originality			

There are 4 criteria to be processed with respect to the "Main Objective". Please provide your pair-wise comparison results in the following table.

Main Objective	Design	Accountability	Outcome	Overall Quality
Design				
Accountability				
Outcome				
Overall Quality				

There are 3 sub-criteria to be processed with respect to "Design" criteria
Please provide your pair-wise comparison results in the following table.

Design	Scope	Hard Problems	Originality
Scope			
Hard Problems			
Originality			

There are 3 sub-criteria to be processed with respect to "Accountability" criteria. Please provide your pair-wise comparison results in the following table.

Accountability	Leverage	Schedule Management	Budget Management
Leverage			
Schedule Management			
Budget Management			

There are 2 sub-criteria to be processed with respect to "Accountability" criteria. Please provide your pair-wise comparison results in the following table.

Outcome	Exploitation Plan	Potential for Uptake
Exploitation Plan		
Potential for Uptake		

Appendix M – Resource Allocation by AHP Rankings

This appendix contains the computation of resource allocations using AHP ranking information.

Next page is the Excel sheet used to compute the amount of DRDC fund allocated to each Thrust. The amount of fund is calculated as a percentage shown above each fund column. This value is calculated by dividing the allocated budget by the total requested fund in each Thrust group. Then each Thrust within a group is awarded the same percentage of what they have asked for.

If the allocated budget is more than the total requested funds (as the case in Thrust group 1), the surplus is carried down to the next Thrust group in the rank. Amount of $0.51M is carried from Thrust group 1 to Thrust group 2 as surplus. The process starts from Thrust group 1 and continues with the next lower ranked Thrust group.

Group1	Thrusts	Req. M$	Awarded (%100) M$
Priority	17	*1.3*	*1.30*
0.215	30	*2.2*	*2.20*
	23	*0.6*	*0.60*
	24	*1.4*	*1.40*
	22	*1.3*	*1.30*
	Total req	6.8	
	Alloc Bud	7.31	(priority*$34M)
	balance	0.51	

Group2	Thrusts	Req. M$	Awarded (%98.77) M$
Priority	6	*2*	1.98
0.184	19	*2*	1.98
	15	*0.75*	0.74
	21	*0.6*	0.59
	2	*1.5*	1.48
	Total req	6.85	
	Alloc Bud	6.256	(priority*$34M)
	Forwarded	*0.51*	
	Total Budget	6.766	
	balance	-0.084	

Group3	Thrusts	Req. M$	Awarded (%61.71) M$
Priority	13	*3*	1.85
0.167	26	*2.5*	1.54
	16	*1.5*	0.93
	1	*1*	0.62
	12	*1.2*	0.74
	Total req	9.2	
	Alloc Bud	5.678	(priority*$34M)
	balance	-3.522	

Group4	Thrusts	Req. M$	Awarded (%68.86) M$
Priority	7	*1.5*	1.03
0.16	3	*1.7*	1.17
	18	*1.3*	0.90
	8	*1.6*	1.10
	9	*0.5*	0.34
	29	*1.3*	0.90
	Total req	7.9	
	Alloc Bud	5.44	(priority*$34M)
	balance	-2.46	

Group5	Thrusts	Req. M$	Awarded (%65.16) M$
Priority	20	*1.8*	1.17
0.138	28	*2.6*	1.69
	5	*1.5*	0.98
	14	*1.3*	0.85
	Total req	7.2	
	Alloc Bud	4.692	(priority*$34M)
	balance	-2.508	

Group6	Thrusts	Req. M$	Awarded (%63.75) M$
Priority	4	*2*	1.28
0.135	25	*1.3*	0.83
	10	*1.3*	0.83
	11	*0.5*	0.32
	27	*2.1*	1.34
	Total req	7.2	
	Alloc Bud	4.59	(priority*$34M)
	balance	-2.61	

Above are excerpts from MS-Excel sheet where the values for DRDC funds were calculated.

The following pages contain the computations carried out in Excel sheets to allocate FTE resources between Thrust groups. For the complete description of the steps please refer to Figure 31 in Chapter 4. The process starts from Thrust group 1 and continues to the next ranked Thrust groups in order. It assigns FTEs of various types to Thrusts based on their share calculated through AHP and availability of the types. Results for Thrust group 6 indicates the case where the requested FTE types are not available and a different type could be assigned as a substitute.

Thrust Group 1:

Requested FTEs:

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
17	3	0	5	3	3	0	11	3	17	0	0
30	7	12	21	6	3	3	4	3	3	0	0
23	0	0	0	0	0	0	0	0	0	0	14
24	0	0	0	0	0	0	0	0	0	4	18
22	0	0	0	3	0	0	0	0	0	3	27

Total FTEs requested: 176
AHP weight: 0.215
FTE share: 137.6
Percentage awarded to each Thrust: %78

Thrust Group 1:

Final resource allocation:

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
17	2.34	0	3.9	2.34	2.34	0	8.58	2.34	13.26	0	0
30	5.46	9.36	16.38	4.68	2.34	2.34	3.12	2.34	2.34	0	0
23	0	0	0	0	0	0	0	0	0	0	10.92
24	0	0	0	0	0	0	0	0	0	3.12	14.04
22	0	0	0	2.34	0	0	0	0	0	2.34	21.06
Remaining	+150.56			+150.92				+121.72		+79.52	

Thrust Group 2:

Requested FTEs:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
6	4	3	24	5	8	4	0	0	12	16	3
19	0	0	0	0	0	3	0	0	0	6	0
15	0	0	0	12	0	0	0	0	0	0	0
21	0	0	0	9	0	0	0	0	0	5	3
2	3	0	0	21	0	0	3	0	0	0	3

Total FTEs requested:	147
AHP weight:	0.184
FTE share:	117.76
Percentage awarded to each Thrust:	%80

Thrust Group 2:

Final resource allocation:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
6	3.2	2.4	19.2	4	6.4	3.2	0	0	9.6	12.8	2.4
19	0	0	0	0	0	2.4	0	0	0	4.8	0
15	0	0	0	9.6	0	0	0	0	0	0	0
21	0	0	0	7.2	0	0	0	0	0	4	2.4
2	2.4	0	0	16.8	0	0	2.4	0	0	0	2.4
Remaining	+123.36			+98.92				+112.12		+50.72	

Thrust Group 3:

Requested FTEs:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
13	4	8	4	3	0	3	12	17	22	5	3
26	0	0	0	0	3	0	0	30	0	4	3
16	0	0	15	3	0	0	3	3	0	0	0
1	0	0	0	6	0	0	0	0	0	0	17
12	0	0	3	3	3	3	8	9	4	3	0

Total FTEs requested: 204
AHP weight: 0.167
FTE share: 106.88
Percentage awarded to each Thrust: %52

Thrust Group 3:

Final resource allocation:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
13	2.08	4.16	2.08	1.56	0	1.56	6.24	8.84	11.44	2.6	1.56
26	0	0	0	0	1.56	0	0	15.6	0	2.08	1.56
16	0	0	7.8	1.56	0	0	1.56	1.56	0	0	0
1	0	0	0	3.12	0	0	0	0	0	0	8.84
12	0	0	1.56	1.56	1.56	1.56	4.16	4.68	2.08	1.56	0
Remaining	+105.68			+72.92				+67.92		+32.52	

Thrust Group 4:

Requested FTEs:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
7	3	0	3	8	0	30	3	0	11	0	0
3	0	0	7	0	0	0	0	26	4	3	0
18	0	0	0	9	3	0	0	0	3	3	0
8	11	0	7	3	0	0	0	0	0	0	0
9	0	0	3	10	0	0	4	0	0	0	0
29	0	5	17	0	3	0	3	0	4	3	4

Total FTEs requested: 193
AHP weight: 0.160
FTE share: 102.4
Percentage awarded to each Thrust: %53

Thrust Group 4:

Final resource allocation:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
7	1.59	0	1.59	4.24	0	15.9	1.59	0	5.83	0	0
3	0	0	3.71	0	0	0	0	13.78	2.12	1.59	0
18	0	0	0	4.77	1.59	0	0	0	1.59	1.59	0
8	5.83	0	3.71	1.59	0	0	0	0	0	0	0
9	0	0	1.59	5.3	0	0	2.12	0	0	0	0
29	0	2.65	9.01	0	1.59	0	1.59	0	2.12	1.59	2.12
Remaining	+76			+32.64				+42.48		+25.63	

Thrust Group 5:

Requested FTEs:

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
20	7	3	3	3	3	0	3	0	0	4	0
28	5	24	0	3	0	0	0	0	0	0	0
5	10	0	3	6	0	0	0	0	0	0	0
14	3	0	3	3	5	7	11	3	9	0	0

Total FTEs requested: 121
AHP weight: 0.138
FTE share: 88.32
Percentage awarded to each Thrust: %73

Thrust Group 5:

Final resource allocation:

Thrusts	*Type1*	*Type2*	*Type3*	*Type4*	*Type5*	*Type6*	*Type7*	*Type8*	*Type9*	*Type10*	*Type11*
20	5.11	2.19	2.19	2.19	2.19	0	2.19	0	0	2.92	0
28	3.65	17.52	0	2.19	0	0	0	0	0	0	0
5	7.3	0	2.19	4.38	0	0	0	0	0	0	0
14	2.19	0	2.19	2.19	3.65	5.11	8.03	2.19	6.57	0	0
Remaining	+31.47			+0.52				+33.72		+22.71	

Thrust Group 6:

Requested FTEs:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
4	3	3	9	4	3	3	7	3	13	3	0
25	3	0	0	3	0	0	0	3	0	17	4
10	5	8	0	4	0	3	0	3	0	4	4
11	6	14	9	3	4	3	3	0	3	0	0
27	9	0	3	5	0	0	0	0	0	3	6

Total FTEs requested: 183
AHP weight: 0.135
FTE share: 86.4
Percentage awarded to each Thrust: %47

Thrust Group 6:

Final resource allocation:

Thrusts	***Type1***	***Type2***	***Type3***	***Type4***	***Type5***	***Type6***	***Type7***	***Type8***	***Type9***	***Type10***	***Type11***
4	1.41	1.41	4.23	1.88	1.41	1.41	3.29	1.41	6.11	1.41	0
25	1.41	0	0	1.41	0	0	0	1.41	0	7.99	1.88
10	2.35	3.76	0	1.88	0	1.41	0	1.41	0	1.88	1.88
11	2.82	6.58	4.23	1.41	1.88	1.41	1.41	0	1.41	0	0
27	4.23	0	1.41	2.35	0	0	0	0	0	1.41	2.82
Remaining	-2.37			-20.63				+21.97		+3.44	

Appendix N – AHP Sensitivity Analysis for Subcriteria

Below graphs are obtained from Expert Choice dynamic sensitivity analysis with respect to subcriteria. The sensitivity analysis for the main criteria are presented in section 4.2. The analysis is performed with respect to Cluster Group 1. The values on the left of the figure shows the limit where ranking is affected.

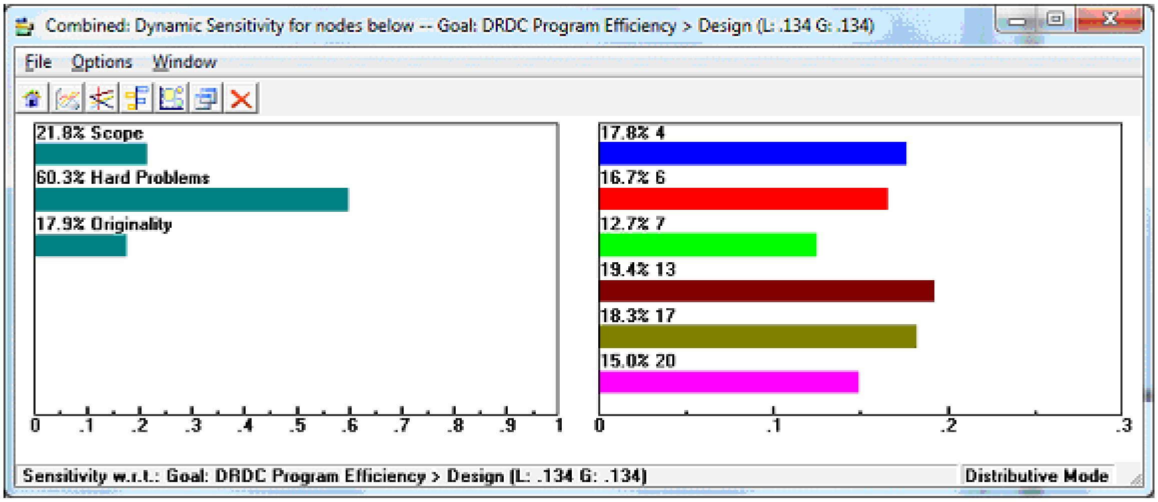


Figure N1. Original ranking of Thrusts in Cluster 1 with criteria under 'Design'

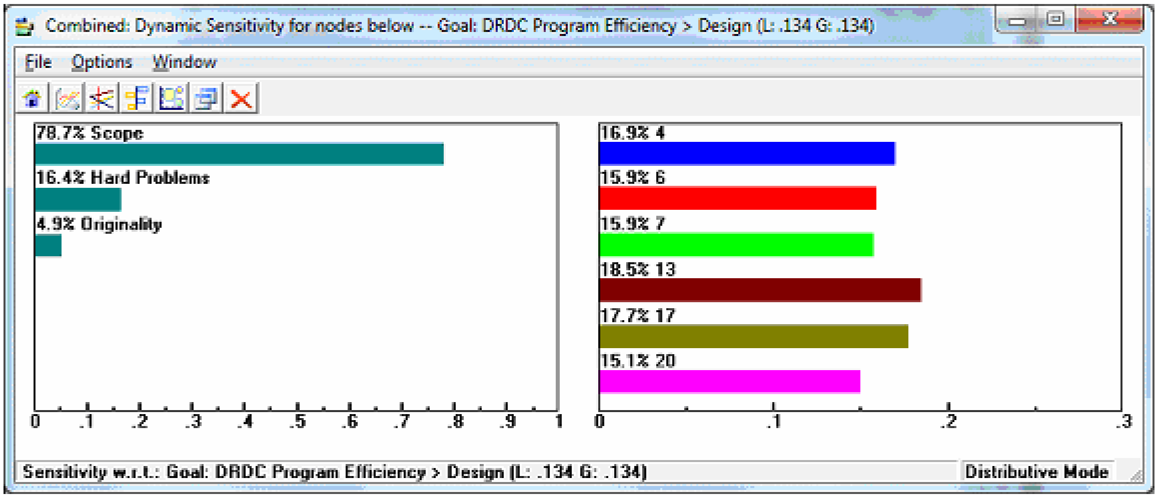


Figure N2. Sensitivity analysis Cluster Group 1 for Scope (Upper limit)

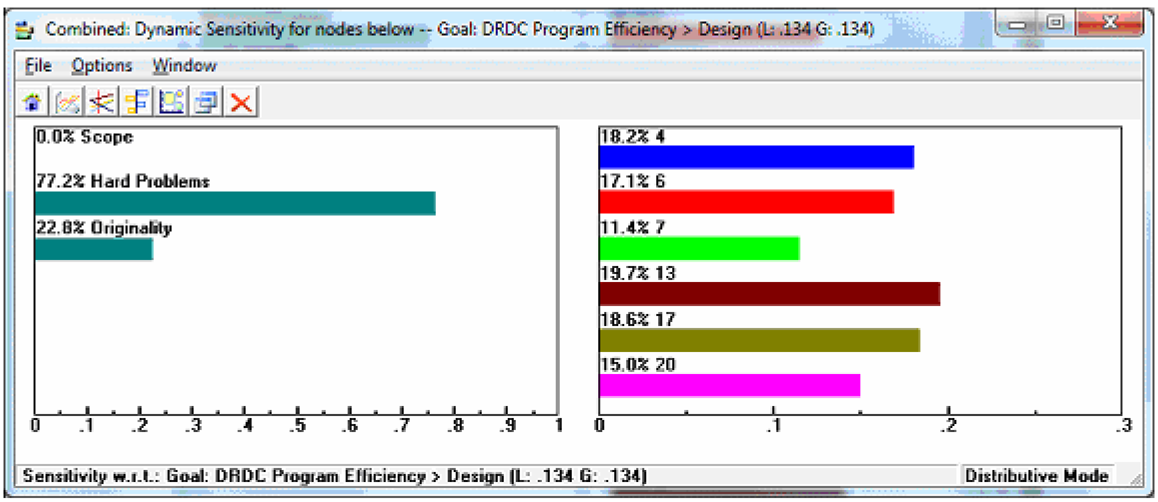


Figure N3. Sensitivity analysis Cluster Group 1 for Scope (Lower limit)

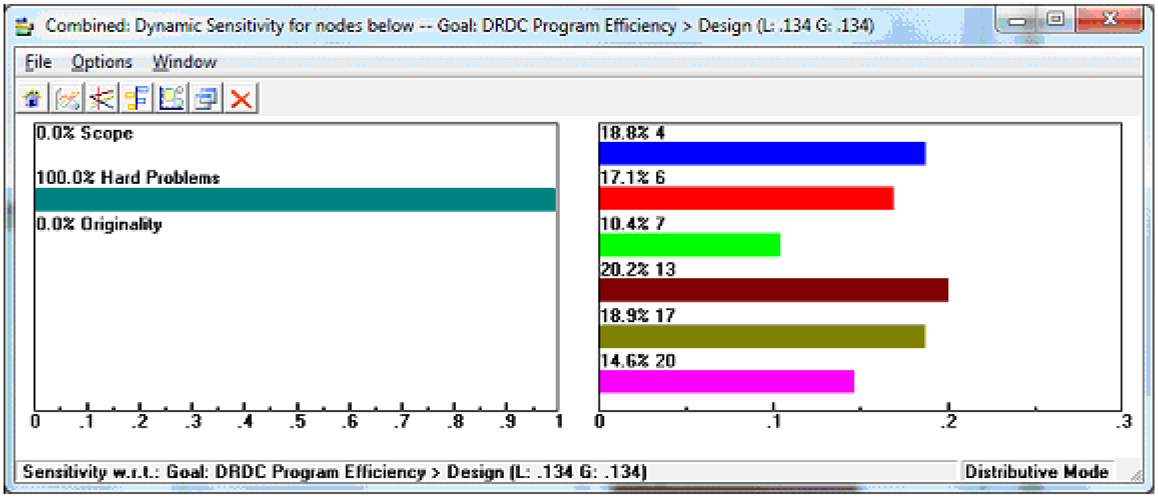


Figure N4. Sensitivity analysis Cluster Group 1 for Hard Problems (Upper limit)

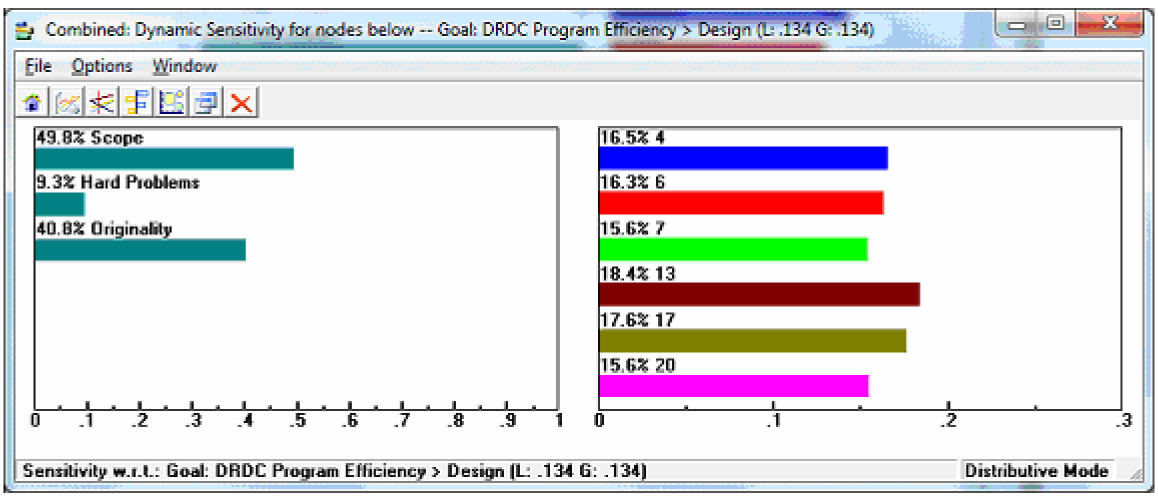


Figure N5. Sensitivity analysis Cluster Group 1 for Hard Problems (Lower limit)

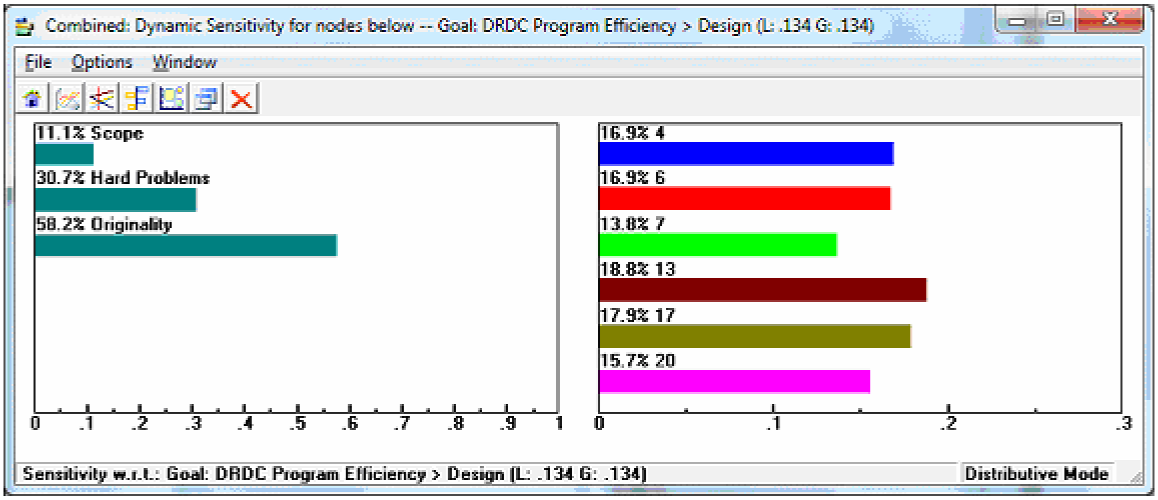


Figure N6. Sensitivity analysis Cluster Group 1 for Originality (Upper limit)

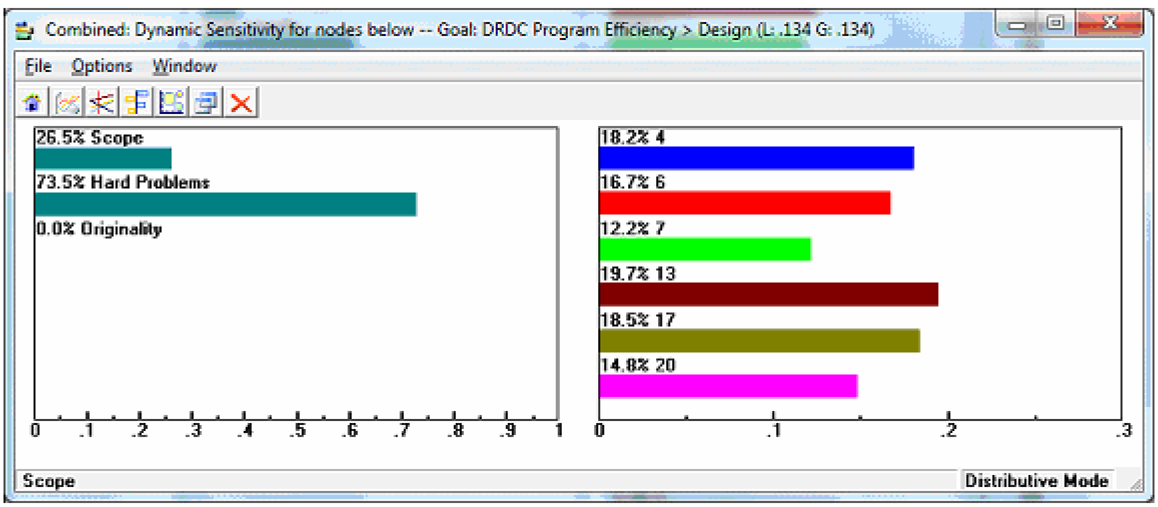


Figure N7. Sensitivity analysis Cluster Group 1 for Originality (Lower limit)

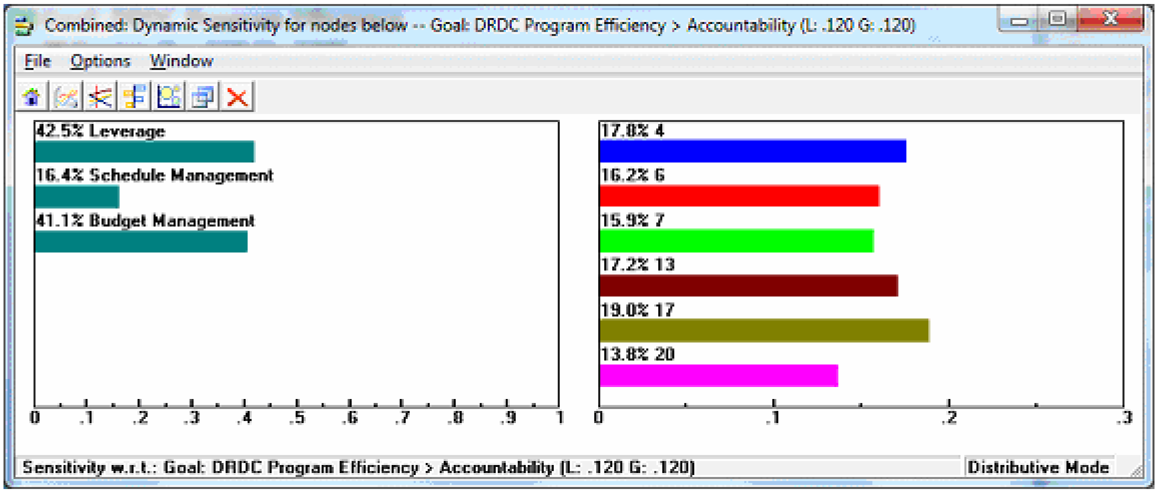


Figure N8. Original ranking of Thrusts in Cluster 1 with criteria under ‘Accountability’

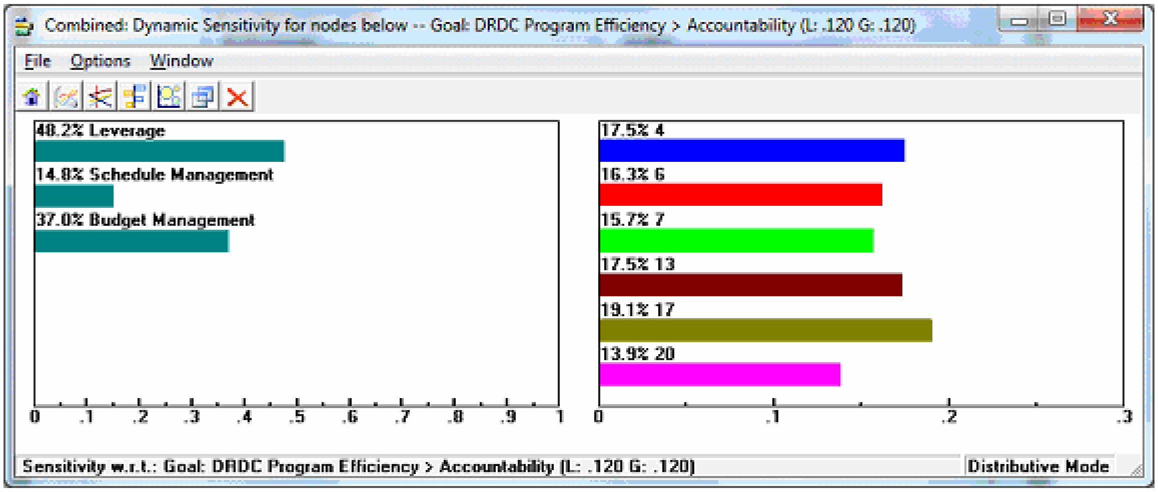


Figure N9. Sensitivity analysis Cluster Group 1 for Leverage (Upper limit)

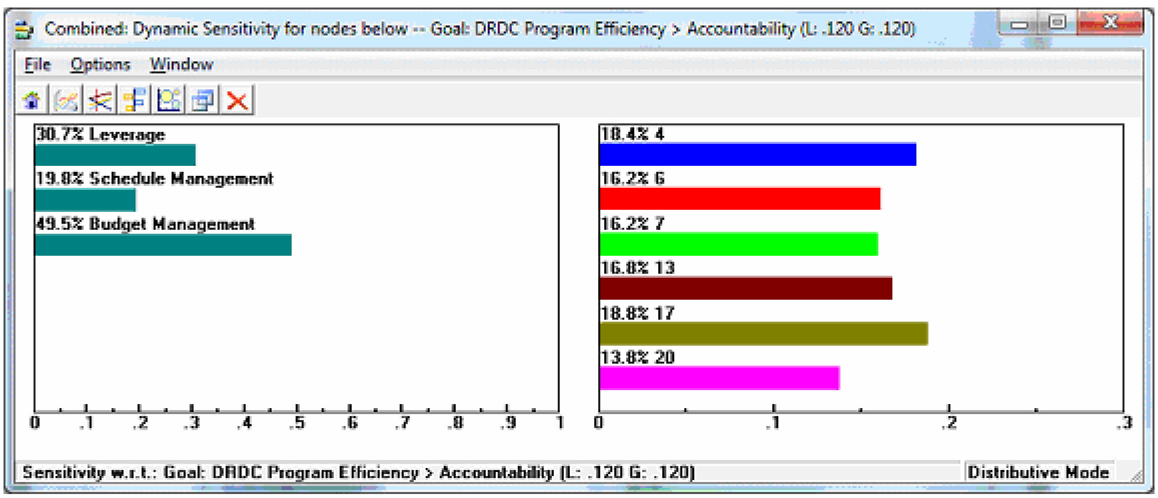


Figure N10. Sensitivity analysis Cluster Group 1 for Leverage (Lower limit)

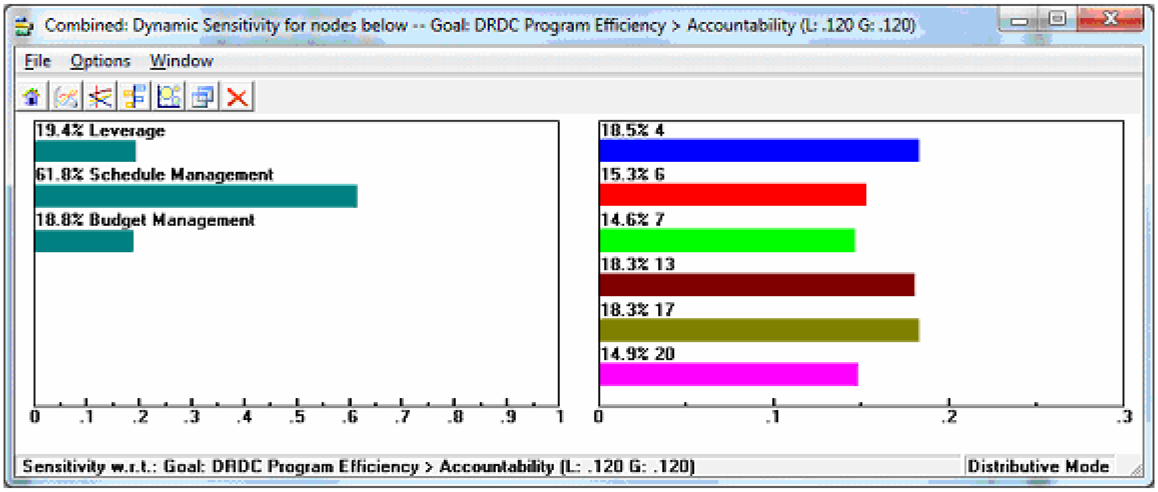


Figure N11. Sensitivity analysis Cluster Group 1 for Schedule Management (Upper limit)

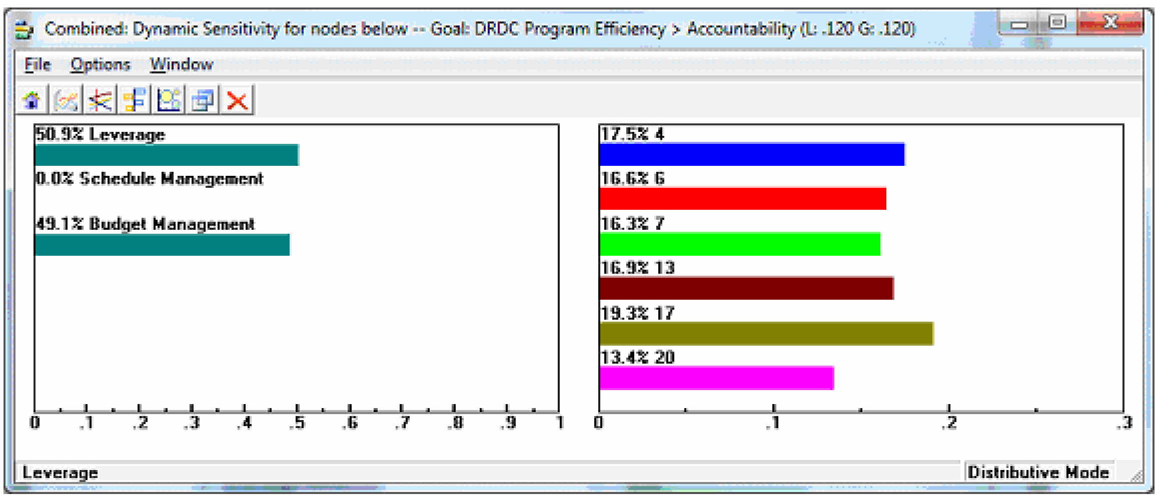


Figure N12. Sensitivity analysis Cluster Group 1 for Schedule Management (Lower limit)

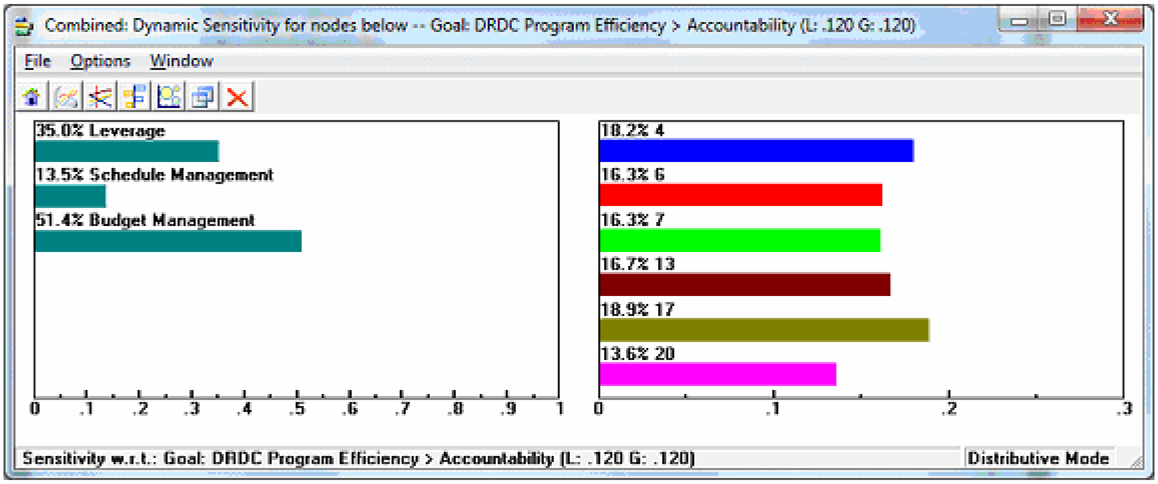


Figure N13. Sensitivity analysis Cluster Group 1 for Budget Management (Upper limit):

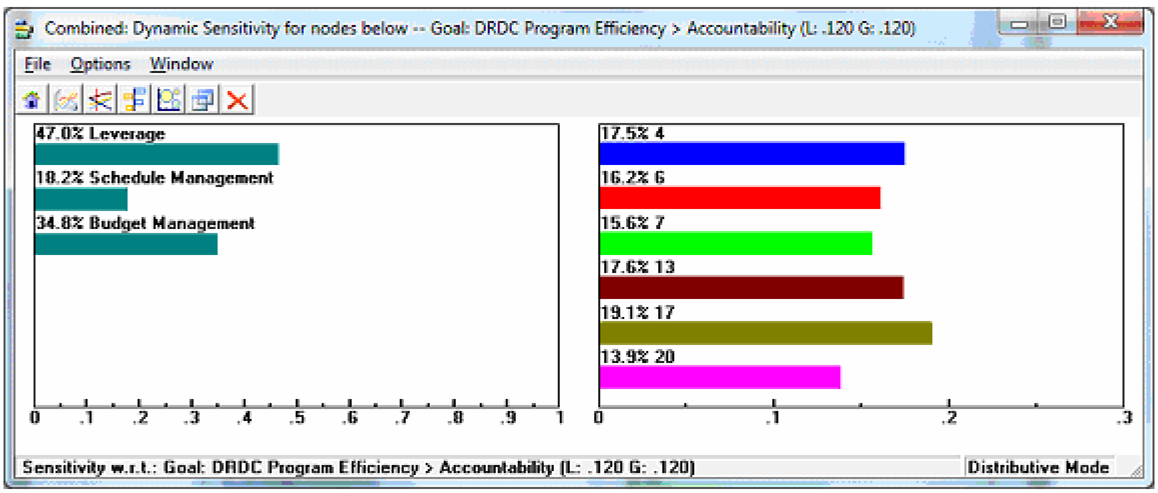


Figure N14. Sensitivity analysis Cluster Group 1 for Budget Management (Lower limit)

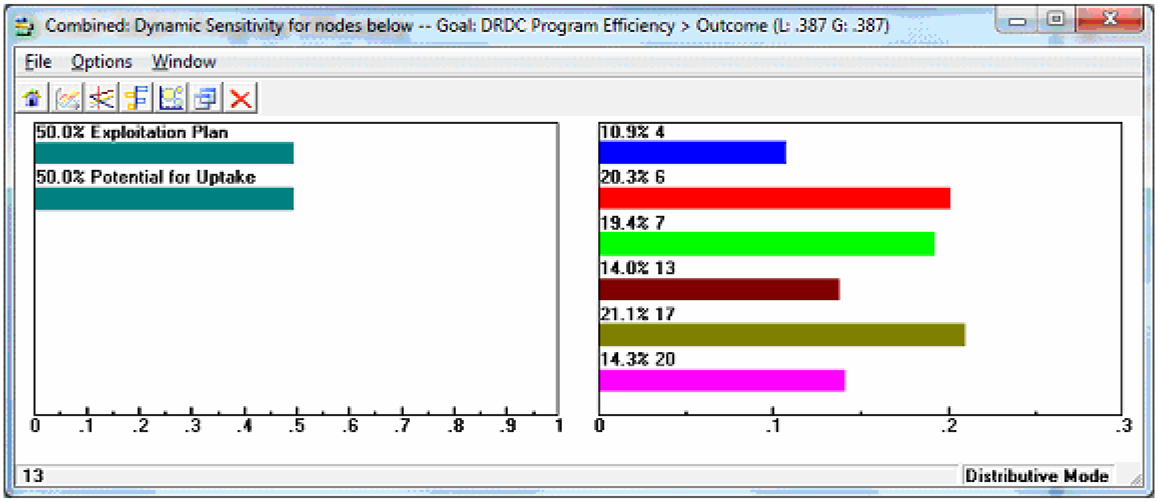


Figure N15, Original ranking of Thrusts in Cluster 1 with criteria under ‘Outcome’

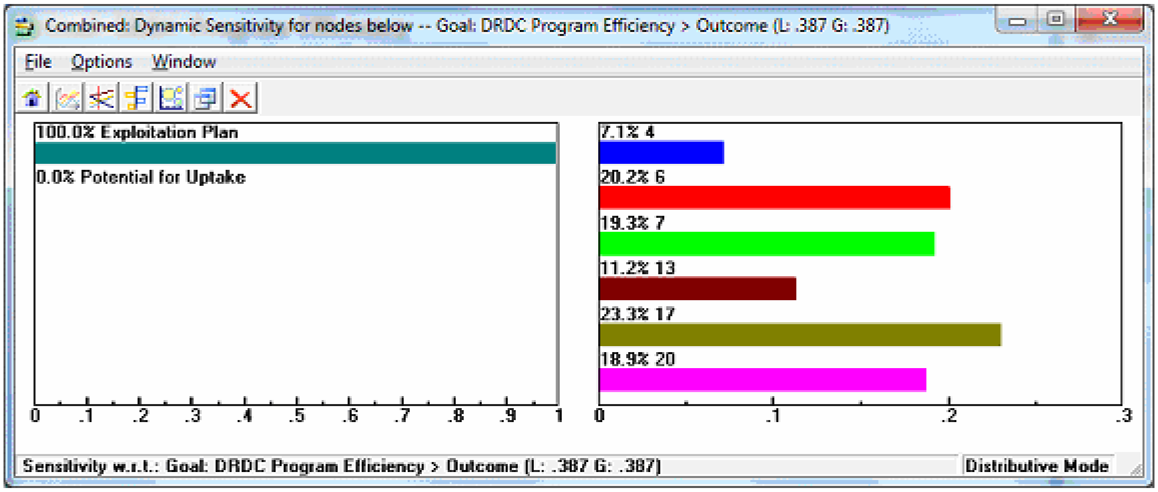


Figure N16. Sensitivity analysis Cluster Group 1 for Exploitation Plan (Upper limit)

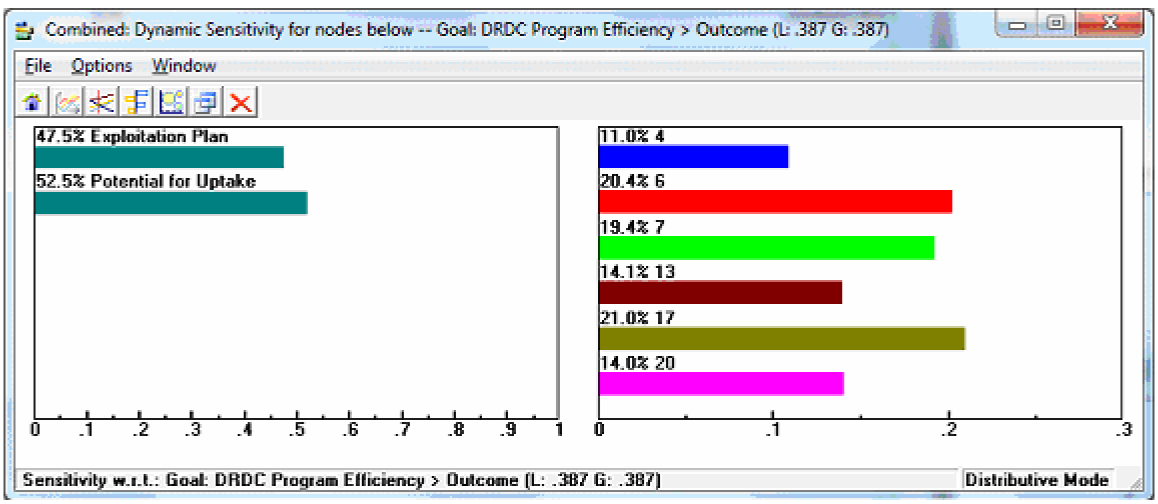


Figure N17. Sensitivity analysis Cluster Group 1 for Exploitation Plan (Lower limit)

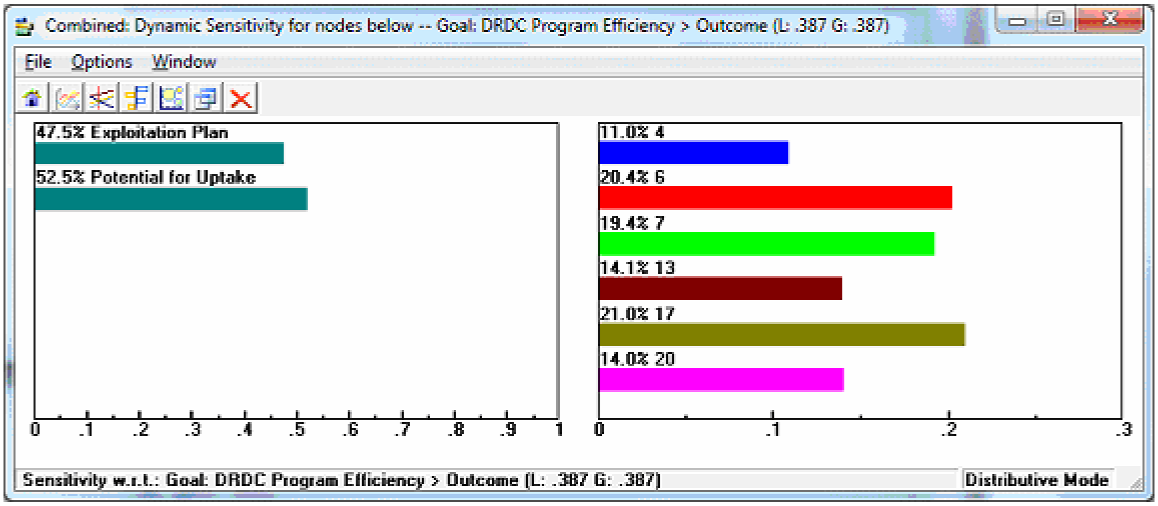


Figure N18. Sensitivity analysis Cluster Group 1 for Potential for Uptake (Upper limit)

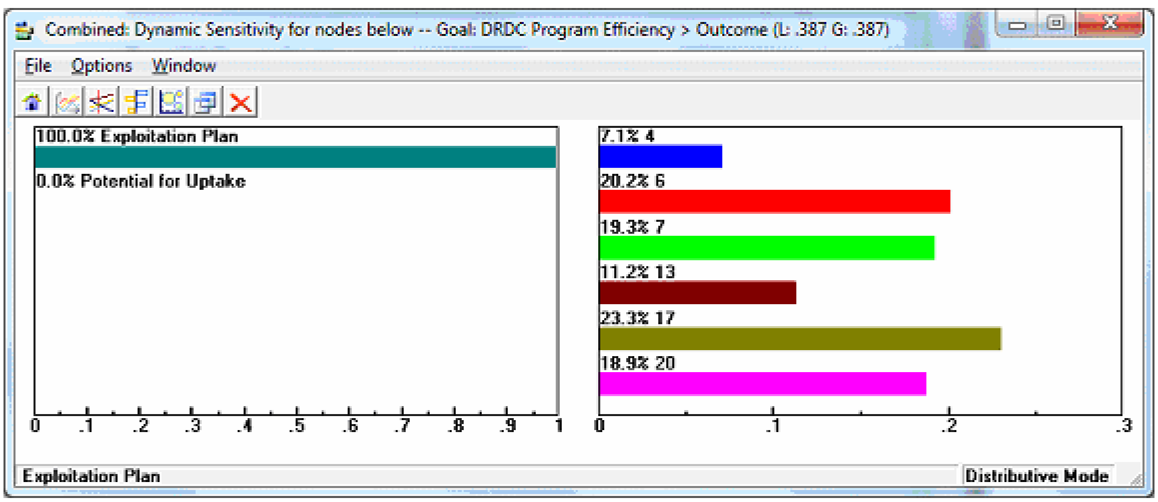


Figure N19. Sensitivity analysis Cluster Group 1 for Potential for Uptake (Lower limit)