A FRAMEWORK FOR PROJECT PORTFOLIO FORMATION USING A HYBRID OF MULTICRITERIA DECISION-MAKING METHODS

A Dissertation Presented

By

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ABSTRACT

The main contribution of this dissertation is the development of a comprehensive framework for the formation of construction project portfolios. The most important phase of project portfolio management is portfolio formation. The survival of organizations depends on selecting the highest value projects considering a restricted budget, and above all organizational goals. A large and far-reaching online survey on portfolio management found that many organizations don’t have a systematic approach in portfolio formation under budget restriction. This finding served as the main impetus for developing a framework for portfolio formation in the field of construction capital projects.

The designed framework selects projects that are better aligned with organizational goals under a budget constraint. This framework creates balance in portfolios in terms of business lines and project types by allocating appropriate budgets among them following strategic objectives. Moreover, a new global risk factor is incorporated in prioritizing projects besides other criteria. The proposed criteria are identified based on the survey and a comprehensive literature review, which showed that different project types have various preferred criteria. The most common finance and economic criteria are internal rate of return, net present value, and return on investment. Other criteria are safety risk, amount of damages (consequential damages), and the degree of riskiness of candidate
projects. A sensitivity analysis on the risk factor’s weight helps to select projects based on organizational risk tolerance level, which may be somewhere on the spectrum from risk-prone to risk-averse. The final step is to check the possible interdependencies among selected projects.

Two multicriteria decision-making methods are used in the designed framework. PROMETHEE is used to prioritize projects considering all the preferred criteria, and analytical hierarchy process is used for the first time to calculate a quantitative risk factor based on qualitative evaluation of risks. A tool called Ex-PROMETHEE is developed to analyze the effects of probabilistic input variables on projects’ ranks. Moreover, a flowchart is also designed to check the interdependencies among selected projects based on the defined interdependency tree to avoid choosing succeeding projects without their proceeding.

The designed framework can be tailored in various construction organizations involved in delivering capital projects considering their goals. This framework ensures the likelihood of success within organizations by allocating resources prudently and doing probabilistic analysis.
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LIST OF ABBREVIATIONS

AHP: Analytical Hierarchy Process

CI: Consistency Index

CP: Compromise Programing

CR: Consistency Ratio

CII: Construction Industry Institute

EHS: Environmental, Health, and Safety

ELECTRE: Elimination and Choice Translating REality

IRR: Internal Rate of Return

IT: Information Technology

MCDM: Multicriteria Decision-Making

NPV: Net Present Value

PMI: Project Management Institute

PROMETHEE: Preference Ranking Organization METHod for the Enrichment of Evaluations

PPM: Project Portfolio Management

RI: Random Consistency Index

ROI: Return on Investment

SD: Standard Deviation
TOPSIS: Technique for Order Preference by Similarity to Ideal Solution

WA: Weighted Average

VICOR: VlseKriterijumska Optimizacija I Kompromisno Resenje
Chapter 1: Introduction

The word “Portfolio” originates from the Italian *portafoglio*, which is made of two words: the *portare* and *foglio*. The former means to carry, and the latter means a leaf or a sheet (Merriam-Webster dictionary). Nowadays, portfolio is used widely in different areas with unique meanings to refer to a variety of items and concepts. Portfolio usually refers to an object (a flat case), a collection, a particular area of responsibility, and a computing tool. The most common meaning of the portfolio refers to a collection. The combination of portfolio with other words such as “project” and “management” created some complex terms such as “Project Portfolio Management (PPM)” and “Portfolio Management” that are used interchangeably for managing multiple projects simultaneously.

Finance portfolio, artist’s portfolio, information technology (IT) portfolio management, patent portfolio, and portfolio life are other examples. Some of these terms are defined in dictionaries (William-Webster dictionary; Oxford advanced learner’s dictionary), for example finance portfolio, artist’s portfolio and carrier portfolio, while other terms have been used in the literature. Portfolio life and portfolio work may be interpreted to be related to a collection of life styles and works (Bourne and Lyons, 2005).
The finance portfolio has a general interpretation which refers to a collection of ways to earn money. William-Webster dictionary defines finance portfolio as “a collection of assets such as stocks, bonds, and cash held by an institution or a private individual.” Investors usually decrease their investment risks considering a collection of investments in different organizations. In this way, if some of the investments crash, the probability of survival increases by compensating their loss from other profitable investments.

The IT portfolio management is an essential component in large or international organizations. Kumar et al. (2008) defines IT portfolio as “the application of systematic management to large classes of items managed by organization IT capabilities.” Examples of IT portfolios are planned initiatives, network based processes and procedures, and ongoing IT software and hardware services on computers. IT portfolio facilitates the connection of organizations’ branches globally, increases the pace of information transformation, reduces the operating cost of organizations, makes the activities recordable, simplifies implementation of processes and procedures, etc.

In the context of project management, the Standard of Portfolio Management by project management institute (PMI) (PMI, 2013a) defines PPM as “a coordinated management of portfolio components to achieve specific organizational goals.” Effective management is possible when an organization uses consistent similar processes, methods, tools, techniques, standards, and technologies to achieve organizational goals.

A distinction should be made here between program and portfolio. A program consists of a collection of related projects that are part of a megaproject, while projects and programs in a portfolio may be independent of each other. According to portfolio
definition in PMI (2013a), a portfolio may consist of other portfolios, programs, and projects (Figure 1.1).

![Portfolio Hierarchy Diagram](image)

Figure 1.1. A Sample of Portfolio Hierarchy (CII IR303-2, 2014)

Two major objectives are followed by using PPM:

- Determine the optimal resources required to best achieve an organization’s operational and financial goals.
- Focus on scheduling, tracking, and controlling activities while considering constraints imposed by customers, strategic objectives, or external real-world factors such as competitors.

Project management office (PMO) is a department within an organization. PMO is responsible for implementing governance and consistent processes to use limited resources among related and unrelated projects and programs. PMO is responsible for selecting the most desirable projects among the list of candidate projects for each portfolio.
The PMI standard cannot be used like a technical standard that includes all the details of a process. It means that some general guidelines are included in the PMI standard that can be considered in establishing PPM; however, organizations should implement an effective PPM model based on their needs and objectives. In a meeting with representatives of 100 organizations, different PPM models are identified among 90% of these organizations (Kendall and Rollins, 2003). The PPM guidelines should be customized in different organizations based on the PMI standard. Payne (1995) estimated that PPM is used for 90% of total dollar value of projects.

Portfolio formation is the first and most important step in the PPM process. Selected projects included in a portfolio may be interrelated or independent but should give the highest value to an organization. The purpose of organizing projects in a portfolio is to facilitate efficient management of these projects to meet strategic objectives. Organizations form their portfolios to reduce their cost while facilitating the communication.

PPM is used in owner and contractor organizations with some differences (CII IR303-2, 2014). Owners usually use PPM to form their portfolios, aiming to achieve their goals with an efficient consumption of resources. Contractors usually do not have goals and objectives in terms of how to invest for survival in the fast growing world. Most of the time, they try to win a bid or negotiate a new contract with a client to increase their profit or at least keep their business and personnel busy all the time. PPM helps contractors to execute projects more efficiently and use resources in an optimal way.
Owners usually form their portfolios according to diverse factors: business line, geographical location, source of budget, or technology. These factors form different portfolios at various levels of a portfolio hierarchy. For example, a pharmaceutical company can form its portfolio based on geographical location and then type of technology. Alternatively, an international oil and gas company may form their portfolios based on the business line and then geographical location. Contractors usually form their portfolios according to their clients’ needs. However, geographical location and business lines are other factors that can affect portfolio formation in contractor organizations; the major factor is the efficient use of their resources.

Forming portfolios correctly helps organizations to boost the efficiency of their resources. Engaging experts in repetitive activities increases their efficiency. In fact, repetitive tasks raise the knowledge and experience of experts over a specific area, so a new similar task will be handled with less effort, less time, and consequently with lower cost.

This dissertation has two main components: 1) A comprehensive survey on PPM supported by the Construction Industry Institute (CII), and 2) a designed project portfolio formation framework. The second component is a new developed framework due to the industry needs, which was identified in the survey. The lack of systematic approach in project prioritization and portfolio formation was the major reason for further research on project portfolio formation as one of the initial and most important steps in portfolio formation.

In research supported by the CII (CII RR303-3, expected 2015), a comprehensive survey was launched for gathering information on project portfolio management. The results of
the survey are explained and summarized in Chapter 2, which gives a general view of portfolio management in various types of organizations. The survey investigates portfolio management in organizations by asking questions in five major areas: 1) Firm information, 2) makeup of a portfolio, 3) current practices, 4) performance metrics, and 5) implementation. The survey results provide a reasonably detailed picture of the state of practice in project portfolio management in the United States. Furthermore, it identifies the obstacles, gaps, and needs for future research in this highly demanding management area.

The project portfolio formation framework is described in Chapter 3. The framework includes all the important factors in creating a high value portfolio that follows the organizational goals. The portfolio formation framework is designed to create a balance in terms of risks, project types, and business lines in such a way that the highest value projects are selected and allocated to portfolios. This process creates optimized project portfolios. Another important factor in project portfolio formation is the interdependency among projects. An approach is proposed to check the interdependencies among projects to avoid wasting of investment by selecting succeeding projects without their preceding.

Chapter 3 includes three sections: the first section describes a designed portfolio formation framework using a hybrid of multicriteria decision-making (MCDM) methods for selecting those projects aligned with organizational goals under budget constraint. The use of MCDM methods is essential for portfolio formation because at the organization level multiple criteria are required in ranking projects due to diversity in businesses, geographical locations, risks, and goals. At the organization level, each project
type may include projects from different business lines if the budget is allocated top-down the portfolio hierarchy. Project types may have several preferred criteria, which have various correlations if they are related to each other. So, precise evaluation of candidate projects needs to contemplate multiple criteria, even though some criteria are in one area. For example, net present value (NPV), return on investment (ROI), and internal rate of return (IRR) can be considered in the process of ranking projects while all these criteria are in the finance and economic area. PROMETHEE is used to rank projects using several criteria in different areas such as finance and economic, safety, and miscellaneous. Moreover, a risk factor is considered as a preferred criterion in prioritizing projects for the first time. The risk factor is calculated based on qualitative evaluations of risks and then converting them to one quantitate value using analytical hierarchy process (AHP). This framework creates balance in terms of business lines and project types by allocating budget among them considering strategic objectives. All the various steps of project prioritization and portfolio formation process are explained in this section.

The second section is related to creating balance in terms of risks in a portfolio. A framework is suggested to calculate a risk factor for each project based on qualitative or quantitative evaluation of various risks. A code is developed based on AHP to convert the qualitative risks to quantitative values in two cases: 1) Qualitative pairwise comparison of risks, and 2) qualitative risks. The risk factor is incorporated in the project ranking step (Figure 3.4) to optimize the rank of high value projects. Considering the organizational intention to be either risk-averse or risk-prone, the weight of a risk factor can be decided using sensitivity analysis.
The third section is related to considering interdependencies among projects within a portfolio. A flowchart is proposed to consider the relationships among projects to form a portfolio. This flowchart checks the interdependencies among projects to ensure that the successor projects are not selected without their predecessor projects. This interdependency check flowchart is designed based on the various possible interdependencies among projects defined on an interdependency tree.

Chapter 4 explains two of the MCDM methods, PROMETHEE and AHP. PROMETHEE is the suggested MCDM method for project ranking in the project portfolio formation framework. AHP is used to convert the qualitative risks to a quantitative risk factor for each project.

An Excel spreadsheet, Ex-PROMETHEE, is designed based on PROMETHEE that allows probabilistic analysis on various input variables of a decision-making problem. Probabilistic analysis is possible by linking the Ex-PROMETHEE to @Risk™ software. The developed Ex-PROMETHEE tool is used to analyze any possible variation in projects’ ranks considering probabilistic input variables and form the portfolios for the case study described in Chapter 5.

A Matlab code is developed for AHP to facilitate the use of this method for project portfolio formation because this method requires numerous calculations, which take time. The main purpose of this code is to calculate a quantitative risk factor using qualitative risks; however, this method is also used to rank projects in the case study. The results of this method are compared with PROMETHEE. PROMETHEE is suggested for project portfolio formation due to three major reasons. First, PROMETHEE has flexibility
on defining preference functions for each criterion. The preference functions show how for one criterion, the difference between the values of two projects can be converted to a 0-1 interval. Second, PROMETHEE gives more consistent results when including all the projects in one portfolio or in various portfolios based on project types. Third, the combination of the Ex-PROMETHEE and @Risk give the ability to have probabilistic analysis on all the input variables such as: values of criteria, weights of criteria, and the thresholds of preference functions.

Chapter 5 includes a case study in an international plastic manufacturing organization. Three cases are considered on this case study to understand that the best way to form portfolios is to categorize projects based on project types. In Case I, all the candidate projects are considered in one bucket. In Case II, candidate projects are categorized in various buckets based on their types, and in Case III, projects are prioritized based on project types with balanced budget on portfolio categories. Of course, Case III is not applicable on this case study because Case III requires projects’ information at the top organization level. This case study is on one of sites of this international organization. A flowchart is used to illustrate various steps of this case.

The two MCDM methods described in previous chapters are used to form an optimized, balanced, and high valued project portfolio while organizational goals are pursued. In Case II, projects are balanced in terms of project types and in Case III, projects are balanced in terms of business lines. In all cases, the selected projects are balanced in terms of risks by doing sensitivity analysis on a risk factor.
Finally, Chapter 6 describes the conclusions on the devised project portfolio formation framework. This chapter also includes suggested future works that can be fulfilled to enrich the implementation of this framework.
Chapter 2: Survey Results on Project Portfolio Management

2.1. Introduction

The increasing use of managing a group of small projects within organizations simultaneously motivated the Construction Industry Institute (CII) to employ a research team on project portfolio management for the first time (Masoumi et al., 2015). The research objectives were defined by an expert team to meet the industry needs. The team was a group of 17 experts in the major owner and contractor organizations and five academics including two students. The research was done in three major steps that an online survey was the initial activity in the first step before interviews. This chapter explains the results of the survey.

Project professionals have a plethora of recommended project management practices available to help them deliver individual projects, but they need to know how to apply these practices when they manage a project portfolio. The CII best practices are currently not specifically applicable for managing multiple projects; however, several of these could be tailored for use within a portfolio of projects. The CII had not investigated how project-level metrics can be useful to assess the overall performance of a portfolio. To address this need, the CII chartered Research Team (RT) 303 to examine the essential question,
“What practices, techniques, processes, and technologies are most effective for managing a portfolio of projects?” In the context of the CII research, a portfolio is defined as a group of projects and/or programs managed by either a project manager or a project director, hereafter referred to as a portfolio manager.

In the context of portfolio management, the specific research objectives were:

- Provide definitions of terms related to the research topic
- Understand the portfolio management problems, including its main differences with management of individual projects
- Understand problems, issues and challenges in the current implementation of best practices in the execution of portfolio management
- Identify major gaps in current best practices as applied to effective portfolio management
- Identify and analyze techniques, technology, tools, metrics and processes recommended for portfolio management
- Understand the major implementation barriers to adopt recommended best practices for portfolio management
- Recommend best practices to help improve overall portfolio management through a well-defined process that is repeatable across portfolios
- Recommend areas of improvement for further research and development

The focus was identifying, adapting, developing and recommending best practices for portfolio management. Literature search and soliciting industry feedback showed that
proven successful practices are not available. However, project portfolio formation and development were important; it was excluded from the scope of the proposed research. The research focus was more on the contractor viewpoint.

The RT 303 consisted of a group of 17 experts from the CII member organizations. Table 2.1 shows the industry research team members and their organizations.

<table>
<thead>
<tr>
<th>No.</th>
<th>Owners</th>
<th>No.</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Architect of the Capitol</td>
<td>1</td>
<td>Jacobs</td>
</tr>
<tr>
<td></td>
<td>Georgia Pacific LLC</td>
<td>2</td>
<td>Hargrove Engineers</td>
</tr>
<tr>
<td>2</td>
<td>ConocoPhillips</td>
<td>3</td>
<td>WorleyParsons</td>
</tr>
<tr>
<td>3</td>
<td>BP Alternative Energy</td>
<td>4</td>
<td>Faithful+Gould</td>
</tr>
<tr>
<td>4</td>
<td>SABIC</td>
<td>5</td>
<td>Fluor Corporation</td>
</tr>
<tr>
<td>5</td>
<td>Irving Oil Limited</td>
<td>6</td>
<td>Parsons</td>
</tr>
<tr>
<td>6</td>
<td>Southern Company</td>
<td>7</td>
<td>URS Corporation</td>
</tr>
<tr>
<td>7</td>
<td>Anheuser-Busch InBev</td>
<td>8</td>
<td>Coreworx, Inc.</td>
</tr>
<tr>
<td>8</td>
<td>BP Project Performance</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1. The Organizations of the Research Team Members

The three academic research team organizations are as follows:

- Northeastern University
- Georgia Institute of Technology
- University of Florida

Two PhD Students from Northeastern University and Georgia Institute of Technology have several contributions in this research, including:
• Design the initial drafts of the survey and the interview questionnaires which were two important and essential tasks

• Launch and manage the online survey using SelectSurvey™ software

• Arrange and analyze rigorously the numerous responses gathered by the online survey

• Analyze the interviews and extract the common practices, software, procedures, and tools related to managing a portfolio of projects

• Identify portfolio metrics and dashboards

• Prepare all the statistical graphs included in the research documents

• Prepare all the survey’s and interviews’ summary reports included in the research documents

• Prepare timely minutes of meetings and manage all the research documents on the myCI

• Participate in the brainstorming sessions by expressing their innovative ideas to come up with better results and enrich the research content

The research goals were covered in three main stages as shown in Figure 2.1. The Survey is included in the “Collect Data” stage prior to interviews and case studies.
The purpose of the online survey was to help in identifying the principle drivers of successful portfolio management and also, the main barriers to successful implementation of portfolio management in various organizations. Another purpose of the survey was to help in screening and identification of the most appropriate firms for in-depth face-to-face interviews.

The online survey questions were designed with the help and participation of all team members. It was initially prepared by one of the team members and then others gave their feedback through emails. The survey was finalized during two face-to-face team meetings. The final version of the survey questionnaire consisted of 28 questions, and it was designed to be completed in less than 30 minutes. The team made a major effort to extend the data collection beyond the CII membership. For this purpose, the Construction Management Association of America (CMAA) was contacted to reach their membership. The CMAA leadership helped reach their membership and encouraged their members to respond to this research effort. The team also tried to reach the members of the
Construction Users Round Table (CURT), and team members helped in identifying individuals who could contribute to this effort.

### 2.2. Categories of questions

The survey questions were divided into five categories listed below:

- Firm information (info)
- Makeup of a portfolio
- Current practices
- Performance metrics
- Implementation

Several questions could receive more than a single response. They asked about portfolio management in different areas such as schedule, cost, cash flow, procurement, resource allocation, communication, quality, scope, change management, safety, risk management, issue management, and key performance indicators. These questions were included in all the categories.

Questions under the “Firm profile” category were designed to collect information regarding the firm types, industry sectors, and the name and role of respondents. The survey was intended to gather information from all types of firms, public and private, CII and non-CII, and owner and contractor. There are six questions under this category.

The “Makeup of the portfolio” category included six questions to get a perspective on portfolios in terms of size, duration, and dollar value. Moreover, other questions asked if
there was at least one manager who managed multiple projects and the title of the individual.

The next category, “Current practices,” included seven questions. These questions attempted to collect information regarding available tools in 13 various areas related to portfolio management. These areas were schedule, cost, cash flow, procurement, resource allocation, communication, quality, scope, change management, safety, risk management, issue management, and key performance indicators. These areas were finalized during the team brainstorming session. Also, the standardization of tools and practices, using the CII best practices, and prioritization of projects, and portfolio manager’s authorities at the portfolio level were also questioned.

One of the goals of the research was to figure out useful applicable metrics in different areas of portfolio management. Six questions asked under the category “Performance metrics” to understand the available metrics in 15 areas including schedule, cash flow, quality, cost, procurement, resource allocation, communication, scope, change management, safety, risk management, issue management, KPIs, overall portfolio health, and success. There were questions about the areas that metrics could be included in a dashboard; moreover, respondents were asked about the importance of including these 15 areas in an ideal dashboard using a five points Likert scale with 1 (least important) and 5 (most important).

The last category was about the portfolio management implementation, and included three questions. The intention of questions was to measure the level of portfolio management success within organizations, to understand the barriers to the successful
application of portfolio management, and to understand any related suggestions or
comments. The respondents were asked if their firm was successful in portfolio
management and to rate the level of success using a five point Likert scale shown below.

- 5 (Best in class)
- 4 (Very)
- 3 (Average)
- 2 (Somewhat)
- 1 (Not at all)

The finalized list of questions and the SelectSurvey™ format of questions are available in
Appendix 1.

2.3. Firm information

The online survey was launched based on the 28 finalized questions using the
SelectSurvey™ tool. The online survey tool SelectSurvey™ was provided by the CII. A list
of emails was gathered using the CII and CMAA data liaisons in various organizations. The
survey was sent to 306 individuals in 251 organizations. This included 130 CII and 121 non-
CII organizations. Every effort was made to increase the response rate by sending follow-
up emails and contacting the potential recipients to encourage them to respond. Besides,
the deadline was extended to ensure that respondents had sufficient time to complete
the questionnaire. The response rate was 45% of email recipients and 36% of
organizations. These rates compare favorably with similar data collection efforts using the online survey tools (Nulty, 2008; Johnson and Owens, 2003; Hamilton, 2011).

The first six questions the “Firms Statistics” are summarized in this section. The statistics on the firms given below briefly describe the firm’s type, industry sectors, and the roles of respondents.

The statistics on those approached to participate in the research and those who did not participate is shown in Figure 2.2.

![Figure 2.2. Online Survey Firms Statistics](image)

Slightly over half of those interviewed were from the CII organizations. The number of the CII and non-CII organizations was 49 and 41, which comprised of 54.4% and 45.6% of the respondents, respectively. More than half of those responded categorized themselves as
owners. There were 53 (58.9%) owners and 37 (41.1%) contractors. Table 2.2 summarizes the number and percentage of respondents in different organizational types.

Table 2.2. The Number and Percentage of Respondents in Various Organizational Types

<table>
<thead>
<tr>
<th>Respondents</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CII</td>
<td>49</td>
<td>54.4%</td>
</tr>
<tr>
<td>Non-CII</td>
<td>41</td>
<td>45.6%</td>
</tr>
<tr>
<td>Owner</td>
<td>53</td>
<td>58.9%</td>
</tr>
<tr>
<td>Contractor/Consultant</td>
<td>37</td>
<td>41.1%</td>
</tr>
</tbody>
</table>

The survey was designed to get a perspective of portfolio management in different industry sectors. Respondents could select as many industry sectors as they were active in. The percentages given on Figure 2.3 for each industry sector are based on 90 organizations attended the survey. More than half of those interviewed are in heavy industry sector as shown in Figure 2.3. Several of the organizations participated in the survey are engaged in more than one sector of the construction industry; hence the percentages sum to well over 100.
Table 2.3 comprises the number of organizations in each industry sector. Some organizations were active in more than one industry sector as mentioned in previous page.

Table 2.3. The Number of Organizations in various Industry Sectors

<table>
<thead>
<tr>
<th>Industry Sector</th>
<th>Infrastructure</th>
<th>Building</th>
<th>Heavy Industrial</th>
<th>Light Industrial</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Organizations</td>
<td>31</td>
<td>28</td>
<td>58</td>
<td>25</td>
<td>19</td>
</tr>
</tbody>
</table>

The number and percentage of respondents in various organizational types for four CII industry sectors and other sector is included in Table 2.4. The highest percentage of respondents in infrastructure, building, and light industrial sectors was from non-CII contractors. The CII owners in heavy industrial sector had the greatest percentage of participants. The CII organizations in heavy and light industrial sectors had more contribution to the survey while non-CII organizations in infrastructure and building...
sectors got higher percentage of involvement. In other sectors, non-CII organizations had little higher participants.

Table 2.4. The Number and Percentage of Respondents in Different Industry Sectors

<table>
<thead>
<tr>
<th></th>
<th>Infrastructure</th>
<th>Building</th>
<th>Light Industrial</th>
<th>Heavy Industrial</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CII Owner</strong></td>
<td>3</td>
<td>9.7%</td>
<td>6</td>
<td>32%</td>
<td>23</td>
</tr>
<tr>
<td><strong>CII Contractor</strong></td>
<td>9</td>
<td>29.0%</td>
<td>4</td>
<td>14.3%</td>
<td>14</td>
</tr>
<tr>
<td><strong>Non-CII Owner</strong></td>
<td>8</td>
<td>25.8%</td>
<td>5</td>
<td>17.9%</td>
<td>8</td>
</tr>
<tr>
<td><strong>Non-CII Contractor</strong></td>
<td>11</td>
<td>35.5%</td>
<td>13</td>
<td>46.4%</td>
<td>13</td>
</tr>
</tbody>
</table>

*: number of respondents  **: percentage of respondents

These statistics prove that portfolio management is an important topic in organizations especially where the amount of investment is considerable. Heavy industrial sectors have considerable amount of investment; therefore, the efficient consumption of resources is more important. In the next sections, the key findings on makeup of portfolio, current practices, performance metrics, and implementation are explained.

2.4. Key findings and statistical trends

Portfolio management is widely being used in organizations. The individuals who manage several projects are project managers in the majority of organizations, while at the top
managerial levels, program managers, portfolio managers, and project directors were also involved in portfolio managements with different responsibilities. Higher managerial levels usually review less detailed reports on portfolios.

2.4.1. Makeup of a portfolio

Almost all organizations responding to the survey had individuals who manage a group of projects. Portfolio management was practiced in 87 (96.7%) organizations, and only three organizations did not use portfolio management extensively. The widespread use of portfolio management indicates the necessity, importance and relevance of this research in all industry sectors.

The three organizations that did not have individuals to manage multiple projects usually had very large projects that were managed by one person. Two of these organizations still had portfolio management for small projects with a total budget of less than $5 million. One of them mentioned that they were working on one project at a time.

Individuals who manage a portfolio of projects have various job titles. The most common title is project manager following by project director, program manager, other, and portfolio manager. Many organizations have people with multiple job titles that manage a group of projects; hence the percentages do not add up to 100 as shown in Figure 2.4.
The authorities of portfolio managers were asked in four different areas:

- Budget
- Work force
- Procurement strategy
- Sequence of execution (schedule adjustment)

Contractors showed that work force and sequence of execution are the top two areas that portfolio managers had authority. Budget and sequence of execution are two top areas that owners selected. The responses to this question showed that the areas that portfolio managers had authority vary and there was no dominant area. The following comments by owners and contractors confirm that there is diversity in the areas that portfolio managers have authorization:

Contractors highlighted that the authorities for their portfolio managers varied for different portfolios. This varies enormously from client to client, even from site to site.
within a client organization. The breadth of portfolio management authorities was mentioned to be very owner dependent. Some owners gave great freedom to the contractors’ portfolio manager, while others retain tight control.

The formation of portfolios was investigated by asking about the typical duration, budget, and the number of projects in a portfolio. There are some trends in the most common number of projects, budget range of projects, and the duration of projects in a portfolio among organizational types that will be explained in the following paragraphs.

The majority of organizations, 54%, do not assign more than 10 projects in a portfolio as shown in Figure 2.5. More than one-third of respondents do not typically allocate more than six projects to a portfolio. The average number of projects in a portfolio is 17 with a standard deviation of 8.7 which shows the wide variation in the typical number of projects in a portfolio. One of the reasons for variation in the number of projects in a portfolio was the respondents’ position. They were from different organizational levels from General Manager to Project Manager, to Project Controls Manager.

![Figure 2.5. Statistics on the Number of Projects in a Portfolio](image-url)
The CII owners typically have portfolios with more than 50 projects while the majority of other organizations have portfolios with less than 6 projects as shown in Table 2.5. The CII owners who responded to the survey were mostly active in heavy industrial sector with periodic maintenance needs; therefore, the typical number of projects in their portfolios was more than 50. The other three types of organizations had portfolios with typically fewer than 6 projects. This may be due to the fact that these projects tend to be larger in size.

| Table 2.5. The Number and Percentage of Typical Number of Projects in a Portfolio |
|---------------------------------|----|----|----|----|----|----|
|                                 | Less than 6 | 6 to 10 | 11 to 20 | 21 to 50 | More than 50 |
| CII Owner                       | #   | %   | #   | %   | #   | %   | #   | %   | #   | %   |
|                                 | 8   | 25.8% | 2   | 6.5% | 8   | 25.8% | 2   | 6.5% | 11  | 35.5% |
| CII Contractor                  | 6   | 35.3% | 5   | 29.4% | 3   | 17.6% | 2   | 11.8% | 1   | 11.8% |
| Non-CII Owner                   | 9   | 47.4% | 4   | 21.1% | 3   | 15.8% | 1   | 5.3%  | 2   | 10.5% |
| Non-CII Contractor              | 8   | 40.0% | 5   | 25.0% | 4   | 20.0% | 2   | 10.0% | 1   | 5.0%  |

Regarding the size of portfolio budget, the highest percentage of organizations reported portfolio budget in excess of $100 million (Figure 2.6). The same percentage of respondents selected two ranges of $10 million to $25 million and $25 million to $50 million. It appears that the size of portfolios is in excess of $10 million most of the time.
Table 2.6 illustrates that the most common portfolio budget range is larger than $100 million among various types of organizations.

<table>
<thead>
<tr>
<th>Table 2.6. The Number and Percentage of Typical Portfolio Budget Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than $5 Million (M)</td>
</tr>
<tr>
<td>#</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>CII Owner</td>
</tr>
<tr>
<td>CII Contractor</td>
</tr>
<tr>
<td>Non-CII Owner</td>
</tr>
<tr>
<td>Non-CII Contractor</td>
</tr>
</tbody>
</table>

Comparing the portfolio budget range with the number of projects in a portfolio, it could be concluded that organizations form their portfolios either with many small projects or a couple of large projects.
Over three-quarters of respondents selected over a year for a typical duration of projects in a portfolio, shown in Figure 2.7. On the other hand, about one-third of respondents had projects that were typically over two years.

![Pie chart](image)

**Figure 2.7. Statistics on Typical Duration of Projects in a Portfolio**

The highest percentage for all types of organizations except non-CII contractor is 12 to 24 months as the typical duration of projects in a portfolio. Table 2.7 indicates that a high percentage of non-CII contractors selected more than 24 months.

<table>
<thead>
<tr>
<th></th>
<th>Less than 6 months</th>
<th>6 to 12 months</th>
<th>12 to 24 months</th>
<th>More than 24 months</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CII Owner</strong></td>
<td>1</td>
<td>5</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>%</td>
<td>3.2%</td>
<td>16.1%</td>
<td>45.2%</td>
<td>35.5%</td>
</tr>
<tr>
<td><strong>CII Contractor</strong></td>
<td>0</td>
<td>6</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>%</td>
<td>0.0%</td>
<td>35.3%</td>
<td>41.2%</td>
<td>23.5%</td>
</tr>
<tr>
<td><strong>Non-CII Owner</strong></td>
<td>0</td>
<td>3</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>%</td>
<td>0.0%</td>
<td>15.8%</td>
<td>57.9%</td>
<td>26.3%</td>
</tr>
<tr>
<td><strong>Non-CII Contractor</strong></td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>%</td>
<td>10.5%</td>
<td>15.8%</td>
<td>31.6%</td>
<td>42.1%</td>
</tr>
</tbody>
</table>

Table 2.7. The Number and Percentage of Typical Duration of Projects in a Portfolio
2.4.2. **Current practices**

The questions in this section were focused on current practices in 12 different areas. There were seven questions that asked about the areas that organizations using tailored, innovative, standard or customized (commercial or custom-built software), and under developed tools and practices on portfolio management. Moreover, the use of the CII best practices for portfolio management was asked to identify any innovative application of the CII project practices for portfolio management. Then, the two last questions on this section were about the authority of portfolio manager, and the use of a formal system for prioritizing projects.

2.4.3. **Tailored tools**

Almost all the organizations with portfolio management practices have tailored tools, techniques, and processes to manage multiple projects together. Three graphs are presented in Figure 2.8; the top one shows the percentage of tailored tools used in each area for portfolio management. The middle one compares tailored tools in the CII and non-CII organizations, and the bottom one compares owners with contractors in using tailored tools for portfolio management.

Even though the number of the CII organizations responding to the survey is higher than non-CII organizations, 49 compare to 41, the top graph indicates that non-CII organizations reported higher rates of customized tools compared to the CII organizations, on most of the areas except Resource Allocation. Only in the area of Resource Allocation, the CII organizations have higher percentage of tailored tools.
Figure 2.8. Percentage of Firms Using Tailored Tools and Processes in Different Areas
Figure 2.8 indicates that the owner organizations have slightly higher rates of using tailored tools, techniques, and processes in Cash Flow, Cost, Procurement, and Scope. In other areas, contractors have considerably higher rates of usage for tailored tools, especially in Quality, Resource Allocation, Risk management, Change Management, Issue Management, Safety, and Communication.

2.4.4. Innovative tools

The majority of organizations used innovative tools and techniques on portfolio management. There were 37 (67%) organizations out of 55 who had innovative practices. Table 2.8 illustrates the breakdown of respondents who have used innovative tools within various types of organizations. The CII owners used innovative tools more than other types of organizations. It should be noted that the term “innovative tools” could be open to interpretation by the respondents. One person’s innovative tool can be common practice to another organization.

Table 2.8. Respondents’ Statistics of Organizations Implemented Innovative Practices

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>CII Owner</td>
<td>16</td>
<td>84.2%</td>
</tr>
<tr>
<td>CII Contractor</td>
<td>5</td>
<td>50.0%</td>
</tr>
<tr>
<td>Non-CII Owner</td>
<td>8</td>
<td>61.5%</td>
</tr>
<tr>
<td>Non-CII Contractor</td>
<td>8</td>
<td>61.5%</td>
</tr>
</tbody>
</table>
There was a variety of answers on the innovative practices. Organizations mostly customized software in the fields of cost control, scheduling, change orders, and information management. The list of software used in customization includes:

- Microsoft Project Portfolio Management
- Primavera-P6
- Primavera Contract Management
- Outsourced based software system from SaaS (Software as a Service)

Other innovative ideas that were used by organizations are the followings:

- Implementing the Earned Value method (EVMS) was practiced in two organizations.
- Managing projects all around the world using an internally developed tool was used in one organization.
- Using innovative methods for Portfolio Management Information System or the Master Integrated Schedule Tool was experienced in some organizations.
- Prioritizing projects based on their influence on safety was another state-of-the-art tool
- Using of apps in the job site is also useful and time saving.
- Automating portfolio management via web-based software was also practiced to increase the efficiency of work. Capital plan budget was automatically tied to portfolio cash flow. What-if scenarios could be proposed by the Portfolio Manager to the Project Managers electronically.
A comparison between owners and contractors highlighted that the use of P6, Portfolio Contract Management, SAP™ portfolio management, and EVMS were common among owners and contractors. Some processes and procedures were specifically common among owners such as outsourcing of software services, standard stage gate process, and balanced scorecard. The Microsoft Project Portfolio Planner was used only in one owner organization. Contractors used several tools such as web based P6, software on iPad, and the master integrated schedule tool. One of the contractors has his own project management software for managing his projects all around the world.

2.4.5. **Standard or Customized Software**

The use of standard or customized tools (commercial or custom-built software), techniques and processes was widespread among organizations in various areas. These areas, specifically listed in the survey questionnaire, are listed below:

- Schedule
- Cost
- Cash flow
- Procurement
- Resource Allocation
- Communication
- Quality
- Scope
- Change Management
- Safety
- Risk Management
- Issue Management

Schedule and cost were selected by both owners and contractors as the areas with the highest software usage. Procurement and cash flow got the third and fourth ranks for
owners while cash flow and resource allocation had similar ranks for contractors. Issue and risk management software had the lowest usage among owners; and for contractors, scope and issue management software. Table 2.9 depicts the usage of software in 12 areas among owners and contractors.

<table>
<thead>
<tr>
<th>No.</th>
<th>Areas</th>
<th>Owners</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schedule</td>
<td>73%</td>
<td>80%</td>
</tr>
<tr>
<td>2</td>
<td>Cost</td>
<td>69%</td>
<td>74%</td>
</tr>
<tr>
<td>3</td>
<td>Cash flow</td>
<td>56%</td>
<td>69%</td>
</tr>
<tr>
<td>4</td>
<td>Procurement</td>
<td>60%</td>
<td>54%</td>
</tr>
<tr>
<td>5</td>
<td>Resource allocation</td>
<td>46%</td>
<td>60%</td>
</tr>
<tr>
<td>6</td>
<td>Communication</td>
<td>54%</td>
<td>54%</td>
</tr>
<tr>
<td>7</td>
<td>Quality</td>
<td>40%</td>
<td>57%</td>
</tr>
<tr>
<td>8</td>
<td>Scope</td>
<td>40%</td>
<td>31%</td>
</tr>
<tr>
<td>9</td>
<td>Change</td>
<td>48%</td>
<td>51%</td>
</tr>
<tr>
<td>10</td>
<td>Safety</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>11</td>
<td>Risk</td>
<td>33%</td>
<td>40%</td>
</tr>
<tr>
<td>12</td>
<td>Issue</td>
<td>29%</td>
<td>34%</td>
</tr>
</tbody>
</table>

The two most common types of software in the 12 areas are listed in Table 2.10. In this table, the word “Internal” means the software was developed internally and could have been based on an off-the-shelf system that was customized for use by the firm.
Table 2.10. The Top Two Popular Software Packages in Each Area for Owners and Contractors

<table>
<thead>
<tr>
<th>No.</th>
<th>Areas</th>
<th>Owners</th>
<th>Common among Owners and Contractors</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schedule</td>
<td>---</td>
<td>Primavera-P6, MSP</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>Cost</td>
<td>SAP</td>
<td>MS-Office</td>
<td>Internal</td>
</tr>
<tr>
<td>3</td>
<td>Cash flow</td>
<td>SAP</td>
<td>MS-Office</td>
<td>Internal</td>
</tr>
<tr>
<td>4</td>
<td>Procurement</td>
<td>SAP</td>
<td>Internal</td>
<td>Smart Plant</td>
</tr>
<tr>
<td>5</td>
<td>Resource allocation</td>
<td>MS-Office</td>
<td>Promavera-P6</td>
<td>Internal</td>
</tr>
<tr>
<td>6</td>
<td>Communication</td>
<td>SharePoint</td>
<td>Email</td>
<td>Internal</td>
</tr>
<tr>
<td>7</td>
<td>Quality</td>
<td>MS-Office</td>
<td>Internal</td>
<td>ISO</td>
</tr>
<tr>
<td>8</td>
<td>Scope</td>
<td>---</td>
<td>Internal, MS-Office</td>
<td>---</td>
</tr>
<tr>
<td>9</td>
<td>Change</td>
<td>---</td>
<td>Internal, MS-Office</td>
<td>---</td>
</tr>
<tr>
<td>10</td>
<td>Safety</td>
<td>Safety Training</td>
<td>Internal</td>
<td>MS-Office</td>
</tr>
<tr>
<td>11</td>
<td>Risk</td>
<td>MS-Office</td>
<td>Internal</td>
<td>Proprietary Software</td>
</tr>
<tr>
<td>12</td>
<td>Issue</td>
<td>MS-Office</td>
<td>Internal</td>
<td>Proprietary Software</td>
</tr>
</tbody>
</table>

Table 2.10 illustrates that contractors had their own internal or proprietary software for different areas. Owners were more inclined toward off-the-shelf software while the internal software was also used in several areas.

Owners also used other software in scheduling; for example, customized spreadsheets, SAP™, Contract Manager™, and in-house developed software packages. Contractors used Contract Manager™, customized spreadsheets, and eBuilder™.

SAP™ was the most widely used software for cost by owners, while it ranked fourth by contractors. Excel spreadsheets are also used commonly by both contractor and owner companies. Other software packages, used by both owners and contractors, were
Excel was the most commonly used tool in the area of cash flow management. Software packages such as SAP™, Primavera™, Timberline™, Cobra™, and CAPEX™ are among tools also used by both parties.

In the area of procurement, Smart Plant Materials, SAP™, Skire Unifier™, and Primavera-P6™ software packages were common among contractors. Besides SAP™, owners used in-house tools for procurement. Owners also utilized other software packages such as Primavera™, Microsoft Office™, and Contract Manager™.

Primavera was among the two top choices of software packages for contractors and owners for resource allocation. Contractors used in-house developed software packages for resource allocation. On the other side, owners used Excel widely. Other software packages used for resource allocation are MS Project™, Staffing Plans, SAP™, eBuilder™, and Scorecard.

Email was the primary communication tool utilized by both owners and contractors. Owner companies tended to use secure information sharing software packages such as SharePoint, while contractors prefer customized internal software for communication. SAP™, Contract Manager™, Skire Unifier™, Oracle Unifier™, sharing websites, and video/audio conferences were also among software and tools used by both parties for communication.

There was significant diversity among software packages and tools used by contractors in the area of quality. In-house developed software packages were the most commonly used
tools by both contractors and owners. ISO™, Score™, eBuilder™, and Contract Manager™ were among other tools that were used by both contractors and owners. Internal procedures and in-house developed software packages were the most commonly used methods by both contractors and owners in the scope area. Microsoft Office™, Primavera™, Contract Manager™, and Capex™ were among other software packages utilized by both owners and contractors.

Owners and contractors gave similar responses on software packages on change management. In-house software packages and internal procedures were the most widely used by both contractors and owners. Microsoft Office™, Contract Manager™, AIA contract software, and Capex™ were among other software packages that contractors and owners utilized.

The in-house developed software packages and internal procedures were the most commonly used methods by both owners and contractors in the area of safety. SAP™ and Microsoft Office were among other software packages that were used by both contractors and owners. The results suggest that commercial software packages are rarely used in this area.

In-house developed software packages and internal procedures were the most widely used methods for risk management by both contractors and owners. Active Risk, Risk Matrix, Crystal Ball, and Pertmaster™ were among other software packages used by both parties.

Internal procedures and in-house developed software packages are the most commonly used tools by contractors for Issue Management. Contract Manager™, eBuilder™, and
Excel spreadsheets are among the software packages that are used by both contractors and owners.

### 2.4.6. Under Development

Two organizations were working to develop and implement a system based on Unifier Portfolio Manager™. It was useful when a financial goal should be set for a group of projects. Some organizations are planning to use server based software such as PMWeb or have used external repository Citrix, eBuilder™, Capex™, and custom access databases. Collaborated workflow using Microsoft SharePoint was also implemented to transfer information among divisions. Promavera-P6™ or other ORACLE™ software in the field of Portfolio Management (Oracle R12) and SAP™ are also commonly used by both parties.

A comparison between contractors and owners show that both were trying to securely share data among their projects and define the work flows. The use of data sharing software such as eBuilder™ and Share Point™ was common among owners and contractors while for this purpose some customized tools were being developed by owners. Owners also used Capex™ and Citrix™ for data sharing. Owners were working to use software such as Oracle Unifier™, Oracle R12™, and SAP™ for managing a group of projects.

### 2.4.7. The CII Best Practices for Portfolio Management

A CII Best Practice is a “process or method that, when executed effectively, leads to enhanced project performance. The CII Best Practices have been proven through
extensive industry use and/or validation” (CII Webpage, 2014). Over two-thirds of respondents, 47 organizations out of 70, had never adapted the CII best practices for portfolio management. The CII owners used the CII best practices for portfolio management more than the CII contractors, and opposite for non-CII owners.

A few organizations used the CII tools for portfolio management. The respondents showed that BMC (a software company) had developed some tools based on the CII best practices. The use of the CII best practices on safety, PDRI, resource allocation, lessons learned, planning for startup, building teams, front end loading (FEL), and front end planning (FEP) were noted by respondents.

A comparison between the CII contractors and owners showed that the use of PDRI was common among owners and contractors. Based on the CII definition, PDRI is a “Front End Planning tool used to measure the level of scope definition” (CII Glossary, 2013). It helps project teams to communicate and identify risks related to project scope definition. One of the owners uses the Independent Project Analysis (IPA) tools and processes that are similar to the CII best practices. On the contractor side, the BMC best practices which are similar to the CII were used. Some contractors considered their clients’ viewpoints and needs to design a customized FEL or FEP process.

### 2.4.8. Project prioritization within portfolios

The majority of organizations, 52.9%, did not use a formal system of project prioritization within their portfolios. The prioritization system was used by the CII and non-CII owners more than contractors. The percentage of owners who used formal prioritization was
higher than those who did not use. The respondents did not specify any standard prioritization method for the projects in a portfolio. Some organizations had established criteria to prioritize projects, but the prioritization method was not stated. Some organizations indicated factors or methods for prioritization such as project deadlines, open communication with client, weekly project meeting, safety, revenue, operation improvements, turnaround date for installation, and resource requirements. These are some simple prioritization methods that were practiced in organizations. Some systematic processes were also reported, using tools such as Work Load Planner, an in-house risk-based system, SaaS™, and StrataJazz™.

2.4.9. Performance Metrics

Six questions were included in this section. These questions asked about measuring portfolio performance in 13 areas, improving metrics on these areas, visualizing the portfolio performance on a scorecard/dashboard, weighting the importance of different areas on a dashboard. The intention of this section was to identify the metrics that organizations use and what information could be included in an ideal dashboard.

2.4.9.1. Portfolio Performance

More than 81% of organizations, 56 in number, who responded to the survey had metrics to measure and monitor the performance of projects at the portfolio level. Over half of the CII organizations that were using portfolio performance measures were owners. The percentage of non-CII owners using portfolio performance measures was also higher than
contractors, 37.5% compare to 34.4%. The following 13 areas were considered in the survey:

- Schedule
- Cost
- Cash flow
- Procurement
- Resource Allocation
- Communication
- Quality
- Scope
- Change Management
- Safety
- Risk Management
- Issue Management
- Key Performance Indicators (KPIs)

The top five areas to measure portfolio performance had similar ranks among both parties. Cost and then schedule were the most selected areas by both owners and contractors. Besides cost and schedule, cash flow, change management, and safety were the other three areas with similar ranks for both parties. Figure 2.9 shows the number of respondents who selected each of the areas to measure their performance at the portfolio level.
Figure 2.9. Statistics on Selected Metrics in Diverse Areas for Measuring Portfolio Performance

The rank of different areas based on the number of respondents from owners and contractors are shown in Table 2.11.
Table 2.11. Rank of Areas for Portfolio Performance Selected by Owners and Contractors

<table>
<thead>
<tr>
<th>Rank</th>
<th>Owners’ Areas</th>
<th>Contractors’ Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cost</td>
<td>Cost</td>
</tr>
<tr>
<td>2</td>
<td>Schedule</td>
<td>Schedule</td>
</tr>
<tr>
<td>3</td>
<td>Cash Flow</td>
<td>Cash Flow</td>
</tr>
<tr>
<td>4</td>
<td>Change Management</td>
<td>Change Management</td>
</tr>
<tr>
<td>5</td>
<td>Safety</td>
<td>Safety</td>
</tr>
<tr>
<td>6</td>
<td>Procurement</td>
<td>Quality</td>
</tr>
<tr>
<td>7</td>
<td>Scope</td>
<td>KPIs</td>
</tr>
<tr>
<td>8</td>
<td>KPIs</td>
<td>Procurement</td>
</tr>
<tr>
<td>9</td>
<td>Resource Allocation</td>
<td>Resource Allocation</td>
</tr>
<tr>
<td>10</td>
<td>Quality</td>
<td>Risk Management</td>
</tr>
<tr>
<td>11</td>
<td>Communication</td>
<td>Communication</td>
</tr>
<tr>
<td>12</td>
<td>Risk Management</td>
<td>Scope</td>
</tr>
<tr>
<td>13</td>
<td>Issue Management</td>
<td>Issue Management</td>
</tr>
</tbody>
</table>

2.4.9.2. Improving Metrics in Various Areas

Owners and contractors have different needs regarding developing metrics in different areas. Less than half of respondents expressed their needs to improve metrics for the 13 areas. The number of owners needing improved metrics was 34 out of 67 while only 29 out of 54 contractors stated the need to have improved metrics. The highest needs to metrics improvement were respectively on resource allocation, schedule, and cash flow for owners; and schedule, resource allocation, and KPIs were identified for contractors. Figure 2.10 shows the number of respondents interested in having improved metrics in various areas to measure the portfolio performance. The number of contractors is more
in the areas of procurement, quality, and other. Some of the metrics included in the other area are listed in Table 2.14.

![Figure 2.10. Areas Need Improved Metrics to Measure Portfolio Performance](image)

Table 2.12 illustrates the rank of various areas that need improved metrics to measure the performance of a portfolio.
Table 2.12. Rank of Areas Selected to Have Improved Metrics for Portfolio Performance

<table>
<thead>
<tr>
<th>Rank</th>
<th>Owners’ Areas</th>
<th>Contractors’ Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Resource Allocation</td>
<td>Schedule</td>
</tr>
<tr>
<td>2</td>
<td>Schedule</td>
<td>Resource Allocation</td>
</tr>
<tr>
<td>3</td>
<td>Cash flow</td>
<td>KPIs</td>
</tr>
<tr>
<td>4</td>
<td>Change Management</td>
<td>Quality</td>
</tr>
<tr>
<td>5</td>
<td>Cost</td>
<td>Risk Management</td>
</tr>
<tr>
<td>6</td>
<td>KPIs</td>
<td>Change Management</td>
</tr>
<tr>
<td>7</td>
<td>Safety</td>
<td>Cost</td>
</tr>
<tr>
<td>8</td>
<td>Risk Management</td>
<td>Procurement</td>
</tr>
<tr>
<td>9</td>
<td>Communication</td>
<td>Communication</td>
</tr>
<tr>
<td>10</td>
<td>Issue Management</td>
<td>Issue Management</td>
</tr>
<tr>
<td>11</td>
<td>Quality</td>
<td>Cash flow</td>
</tr>
<tr>
<td>12</td>
<td>Scope</td>
<td>Scope</td>
</tr>
<tr>
<td>13</td>
<td>Procurement</td>
<td>Safety</td>
</tr>
<tr>
<td>14</td>
<td>Other</td>
<td>Other</td>
</tr>
</tbody>
</table>

2.4.9.3. Dashboards

A performance dashboard can be defined as “a multilayered application built on a business intelligence and data integration infrastructure that enables organizations to measure, monitor, and manage performance more effectively” (Eckerson, 2010). Only a few studies have focused on performance dashboards in the construction domain (Lamptey and Fayek, 2012; Suk et al., 2011; Furneaux et al., 2010; Pantea and Pelin, 2010; Alvarado et al., 2004). Among these studies, Suk et al. (2012) and Alvarado et al. (2004) studied performance dashboards for construction project portfolios. Suk et al. (2012) created a performance dashboard for a pharmaceutical project benchmarking program. This work was done as part of a benchmarking study supported by the CII. They used 198
pharmaceutical capital projects (submitted by 12 companies) to develop a performance dashboard.

The survey showed that the majority of organizations, 59.1%, use some sort of dashboard to visualize the portfolio performance. A higher percentage of the CII owners and contractors had a scorecard/dashboard compare to non-CII owners and contractors. Table 2.13 depicts the number and percentage of respondents using a dashboard.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th></th>
<th>No</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>%</td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>CII Owner</td>
<td>16</td>
<td>45.7%</td>
<td>3</td>
<td>8.6%</td>
</tr>
<tr>
<td>CII Contractor</td>
<td>8</td>
<td>22.9%</td>
<td>8</td>
<td>22.9%</td>
</tr>
<tr>
<td>Non-CII Owner</td>
<td>9</td>
<td>29.0%</td>
<td>7</td>
<td>22.6%</td>
</tr>
<tr>
<td>Non-CII Contractor</td>
<td>6</td>
<td>19.4%</td>
<td>9</td>
<td>29.0%</td>
</tr>
</tbody>
</table>

Cost and schedule are the top two areas for which owners and contractors have metrics in dashboards. Besides cost and schedule, contractors chose change management as third top area, while owners selected safety and cash flow as the third and fourth top areas. Table 2.14 includes some of the metrics in 15 different areas that organizations had used.
Table 2.14. List of Metrics Used for Measuring Portfolio Performance in Different Areas

<table>
<thead>
<tr>
<th>Owners</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule</td>
<td></td>
</tr>
<tr>
<td>• Milestone schedule vs. baseline</td>
<td>• Float Trend</td>
</tr>
<tr>
<td>• Milestone tracking, Value of Plant placed in service on time</td>
<td>• Critical path movements</td>
</tr>
<tr>
<td>• Cycle time index compared to industry; actual schedules to estimated schedules</td>
<td>• Included / SPI</td>
</tr>
<tr>
<td>• Schedule conformance</td>
<td>• Dates</td>
</tr>
<tr>
<td>• Monthly monitoring, S curve</td>
<td>• Days ahead / behind schedule</td>
</tr>
<tr>
<td>• Trend analysis of schedule completion</td>
<td>• Microsoft Project</td>
</tr>
<tr>
<td>• Actual versus committed start-up date</td>
<td>• Key milestone status, progress curve, high-level schedule</td>
</tr>
<tr>
<td>• Red/green/yellow - on track versus overall schedule or not</td>
<td>• Days behind, milestones missed, float loss, etc.</td>
</tr>
<tr>
<td>• SPI</td>
<td>• MS Excel</td>
</tr>
<tr>
<td>• Submittal and review time. completion on time</td>
<td>• Progress against milestones by project</td>
</tr>
<tr>
<td>• Days project is opened</td>
<td>• Planning and execution</td>
</tr>
<tr>
<td>• Schedules of 15-20 projects are reviewed by management on a monthly basis</td>
<td>• Exception reporting</td>
</tr>
<tr>
<td>• Balanced Scorecard with predefined weighting factors</td>
<td>• Schedule performance index</td>
</tr>
<tr>
<td>• Stoplight; against original and latest approved baseline</td>
<td></td>
</tr>
<tr>
<td>• On schedule</td>
<td></td>
</tr>
<tr>
<td>Cash flow</td>
<td></td>
</tr>
<tr>
<td>• Planned vs. actual (3)</td>
<td>• Free cash flow</td>
</tr>
<tr>
<td>• Monthly cash flow</td>
<td>• Actual cash flow vs. projected cash flow (2)</td>
</tr>
<tr>
<td>• Monthly spend versus plan, year to date spend versus plan</td>
<td>• Planned v. actual cash use - monthly, quarterly</td>
</tr>
<tr>
<td>• Fiscal year spend</td>
<td>• MS Excel</td>
</tr>
<tr>
<td>• Quarterly forecast accuracy</td>
<td>• Total annual spending on the program</td>
</tr>
<tr>
<td>• Balanced Scorecard with predefined weighting factors</td>
<td>• DSO</td>
</tr>
<tr>
<td>• Baseline vs. cash flow (2)</td>
<td></td>
</tr>
<tr>
<td>• Under over cash flow targets</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.14. List of Metrics Used for Measuring Portfolio Performance in Different Areas (Cont.)

<table>
<thead>
<tr>
<th>Owners</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quality</strong></td>
<td><strong>Contractors</strong></td>
</tr>
<tr>
<td>• # of defects</td>
<td>• Quality issues for construction</td>
</tr>
<tr>
<td>• Operability</td>
<td>• NCRs</td>
</tr>
<tr>
<td>• Number of open deficiencies more than days and repeated ones</td>
<td>• MS Excel</td>
</tr>
<tr>
<td></td>
<td>• Measure rework</td>
</tr>
<tr>
<td>• Estimate vs. actual or forecast (2)</td>
<td>• % of budget/costs</td>
</tr>
<tr>
<td>• Cost vs. approved</td>
<td>• CPI, Cost Performance Index (2)</td>
</tr>
<tr>
<td>• Cost effectiveness index compared to industry; actual costs to estimated costs</td>
<td>• Dollars</td>
</tr>
<tr>
<td>• Cost conformance</td>
<td>• Actual earned value vs. projected cash flow</td>
</tr>
<tr>
<td>• Monthly monitoring, real vs. budget</td>
<td>• Excel spreadsheet, custom</td>
</tr>
<tr>
<td>• Performance to budget and projection of cost to complete</td>
<td>• Current cost forecast</td>
</tr>
<tr>
<td>• Actual vs. budget</td>
<td>• Track change order cost</td>
</tr>
<tr>
<td>• TIC versus approved - red/green/yellow</td>
<td>• Cost per unit and productivity</td>
</tr>
<tr>
<td>• CPI</td>
<td>• MS excel</td>
</tr>
<tr>
<td>• Completion within % of original budget</td>
<td>• Actual cost vs. planned by project</td>
</tr>
<tr>
<td>• % spent, % over/under appropriations amount</td>
<td>• Monthly cost analysis</td>
</tr>
<tr>
<td>• Balanced scorecard with predefined weighting factors</td>
<td>• Exception reporting plus the value of innovations. Crew cost/hr</td>
</tr>
<tr>
<td>• Monthly and YTD approved, committed, and spent total</td>
<td></td>
</tr>
<tr>
<td>• Stoplight; against original and latest approved baseline</td>
<td></td>
</tr>
<tr>
<td>• Over/under budget</td>
<td></td>
</tr>
<tr>
<td><strong>Scope</strong></td>
<td><strong>Owners</strong></td>
</tr>
<tr>
<td>• RFI’s</td>
<td></td>
</tr>
<tr>
<td>• Monthly monitoring</td>
<td></td>
</tr>
<tr>
<td>• % of error and omission change orders</td>
<td></td>
</tr>
<tr>
<td>• Number of Riders (cost overruns beyond appropriations amount)</td>
<td></td>
</tr>
<tr>
<td>• Balanced Scorecard with predefined weighting factors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Summary scope statement, discussion of any scope changes that may occur</td>
</tr>
</tbody>
</table>
Table 2.14. List of Metrics Used for Measuring Portfolio Performance in Different Areas (Cont.)

<table>
<thead>
<tr>
<th>Owners</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Allocation</td>
<td>Resource Allocation</td>
</tr>
<tr>
<td>• Project team member turn-over</td>
<td>• % of budget/man hours and % utilization of key employees</td>
</tr>
<tr>
<td>• Engineering hours</td>
<td>• Custom access database</td>
</tr>
<tr>
<td>• Capital efficiency/person year over year</td>
<td>• Planned vs. actual resource histograms</td>
</tr>
<tr>
<td></td>
<td>• MS Excel</td>
</tr>
<tr>
<td></td>
<td>• Local vs. remote/work share</td>
</tr>
<tr>
<td>Procurement</td>
<td>Procurement</td>
</tr>
<tr>
<td>• Delivery vs. schedule</td>
<td>• Low cost country participation</td>
</tr>
<tr>
<td>• Monthly monitoring</td>
<td>• Percent of anticipated procurement (based on budget dollars)</td>
</tr>
<tr>
<td>• Number of bidders and bid amount vs. engineering estimate</td>
<td>• Status of key items (ordering, delivery dates)</td>
</tr>
<tr>
<td></td>
<td>• # of projects let on time</td>
</tr>
<tr>
<td></td>
<td>• MS Excel</td>
</tr>
<tr>
<td></td>
<td>• PO's issued vs. plan</td>
</tr>
<tr>
<td></td>
<td>• Locally sourced vs. total procurement</td>
</tr>
<tr>
<td>Communication</td>
<td>Communication</td>
</tr>
<tr>
<td>• Number of DCR's issued and their status as far as open or closed</td>
<td></td>
</tr>
<tr>
<td>• RFIs, submittals, field change orders, meeting minutes, contract manger</td>
<td></td>
</tr>
<tr>
<td>Risk Mngt.</td>
<td>Risk Mngt.</td>
</tr>
<tr>
<td>• Summary of risk issues and response</td>
<td>• Status of major risks (readiness for response, mitigation steps, etc.)</td>
</tr>
<tr>
<td>• Monthly monitoring</td>
<td>• MS Excel</td>
</tr>
<tr>
<td>Issue Mngt.</td>
<td>Issue Mngt.</td>
</tr>
<tr>
<td></td>
<td>• Action item reports</td>
</tr>
<tr>
<td></td>
<td>• List/discussion of current project issues</td>
</tr>
</tbody>
</table>
Table 2.14. List of Metrics Used for Measuring Portfolio Performance in Different Areas (Cont.)

<table>
<thead>
<tr>
<th>Owners</th>
<th>Contractors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change Management (Mngt.)</td>
<td>Listing of COs and claims</td>
</tr>
<tr>
<td>• Scope changes (2)</td>
<td>• Cost variations</td>
</tr>
<tr>
<td>• Oracle change requests</td>
<td>• Status of changes (number of amount pending, in process &amp; approved), Approved changes versus contingency rundown (3)</td>
</tr>
<tr>
<td>• % of changes compared to the base contract</td>
<td>• MS Excel</td>
</tr>
<tr>
<td>• Change orders</td>
<td>• Change log maintained to document project growth from as bid</td>
</tr>
<tr>
<td>• Number of change orders per project, % of added cost to original contract</td>
<td>• Total changes as % original approved budget</td>
</tr>
<tr>
<td>• Project count</td>
<td></td>
</tr>
<tr>
<td>• Pending change order, pending change orders, potential claims, contract manger</td>
<td></td>
</tr>
<tr>
<td>• Balanced scorecard with predefined weighting factors</td>
<td></td>
</tr>
</tbody>
</table>

| Safety | |
|--------| |
| • Safety incidents and statistics | Monitor success |
| • IFR, incidents, most frequent contributing cause | Client survey post project to learn from events |
| • Fatalities, RIFR | Current safety performance statistics - OSHA recordable, Days away from work |
| • Safety performance | • Incidents |
| • 12 month moving average of RIR and DAIR | • Standard TRIF metrics |
| • First aid cases, recordable injuries, lost work day injuries, hours worked | |
| • Just starting to report injuries on a portfolio level | |
| • Number of near misses, number of incidents | |
| • Balanced scorecard with predefined weighting factors | |

<table>
<thead>
<tr>
<th>KPI</th>
<th>Multiple</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Balanced scorecard with predefined weighting factors</td>
<td>Cost, schedule, safety (and quality) KPI's for project - planned v. actual performance</td>
</tr>
<tr>
<td></td>
<td>MS Excel</td>
</tr>
</tbody>
</table>
Safety, cost and schedule were the top three areas that owners and contractors chose in an ideal dashboard. Therefore, an ideal dashboard should at least cover these three areas. Table 2.15 indicates the ranks and quantitative evaluations of areas to be included in an ideal dashboard. The scores were provided by respondents based on a five point Likert scale from 1 (least important) to 5 (most important).
Table 2.15. Ranks and Importance of Different Areas on an Ideal Scorecard/Dashboard

<table>
<thead>
<tr>
<th>Rank</th>
<th>Owners’ Areas</th>
<th>Importance</th>
<th>Contractors’ Areas</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cost</td>
<td>4.54</td>
<td>Safety</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>Safety</td>
<td>4.36</td>
<td>Cost</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>Schedule</td>
<td>4.22</td>
<td>Schedule</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>Success</td>
<td>4.10</td>
<td>Change Management</td>
<td>4.3</td>
</tr>
<tr>
<td>5</td>
<td>Cash Flow</td>
<td>3.89</td>
<td>Quality</td>
<td>4.3</td>
</tr>
<tr>
<td>6</td>
<td>Quality</td>
<td>3.89</td>
<td>Success</td>
<td>4.3</td>
</tr>
<tr>
<td>7</td>
<td>Change Management</td>
<td>3.84</td>
<td>Portfolio Health</td>
<td>4.2</td>
</tr>
<tr>
<td>8</td>
<td>Scope</td>
<td>3.79</td>
<td>KPIs</td>
<td>4.1</td>
</tr>
<tr>
<td>9</td>
<td>Portfolio Health</td>
<td>3.71</td>
<td>Scope</td>
<td>4.0</td>
</tr>
<tr>
<td>10</td>
<td>Risk Management</td>
<td>3.71</td>
<td>Risk Management</td>
<td>3.9</td>
</tr>
<tr>
<td>11</td>
<td>Resource Allocation</td>
<td>3.67</td>
<td>Communication</td>
<td>3.9</td>
</tr>
<tr>
<td>12</td>
<td>Communication</td>
<td>3.58</td>
<td>Resource Allocation</td>
<td>3.8</td>
</tr>
<tr>
<td>13</td>
<td>Issue Management</td>
<td>3.55</td>
<td>Issue Management</td>
<td>3.7</td>
</tr>
<tr>
<td>14</td>
<td>KPIs</td>
<td>3.48</td>
<td>Cash Flow</td>
<td>3.7</td>
</tr>
<tr>
<td>15</td>
<td>Procurement</td>
<td>3.35</td>
<td>Procurement</td>
<td>3.7</td>
</tr>
</tbody>
</table>

2.4.10. Implementation

In this section, respondents evaluated the success of portfolio management implementation within their organizations. Moreover, they highlighted the barriers in implementing portfolio management.

Almost half of organizations rated the portfolio management as “average” in their organization (Figure 2.11), while less than two percent rated the implementation of portfolio management in their organizations as “excellent”.
The respondents identified the following barriers in the implementation process:

- Lack of industry standards, best practices and available training
- Unclear objectives and priorities
- Lack of common code structure
- Cost of implementation (Software, etc.)
- Lack of management support or direction
- Management interference (Micro-management)
- Lack of awareness of value added
- Lack of previous success
- Other
The respondents’ opinions on each of the above areas are expanded below:

**Lack of industry standards and best practices and available training**

- There are no comprehensive standards or best practices
- Even though there are some tools and best practices, they require customization so that they can be applied to each case
- Several companies appear not to have enough information in this field and they do not know how they can improve their current best practices

**Unclear objectives and priorities**

- Prioritization is the main challenge among companies
- There are no written objectives and the prioritization changes over time
- Sometimes the prioritization criteria are not comprehensive and conflict developers between departments

**Lack of common code structure**

- No consistency between different departments within some organizations regarding cost codes
- No standard requirements among owners

**Cost of implementation**

- Software is expensive and needs too much customization
- Data is not centralized and cannot be passed among projects easily
- Software is not appropriate for the needs and size of the projects

**Lack of management support or direction**
• There are conflicting ideas among managers at different levels

• The managers’ knowledge is not the same and sometimes they resist any change in the system as the benefit to cost ratio cannot be quantified

**Management interference**

• The objectives are not clear for managers

• The organizational structure is not appropriate

**Lack of awareness of value added**

• It is hard to quantify the value added to the company

• The knowledge of senior managers is also important for improvement in Portfolio Management

**Lack of previous success**

• Commercial and custom tools have sometimes not been effective

**Other**

• Most of the items listed under “Other” are the same as those stated above

• Variety of the owners and project types inside the portfolio can affect portfolio success

• In very large organizations it is difficult to have one standardized system

• Resources are limited

Some additional suggestions and comments were given to improve the portfolio management within organizations:

• Each business requires its own set of standards for portfolio management
• The standards need to have flexibility because of diversity in organizations

• The competency and efficiency of a portfolio team has great influence on the outcome

• Sometimes in large companies there is no identifiable source of decision-making for the projects

• The use of apps on job sites can be helpful to save cost and time

• IPA can be useful for mega-projects

2.5. Conclusions

Portfolio management is used by almost all of the organizations that participated in the survey. The majority of firms are utilizing software tools to better manage their project portfolios. The survey has identified various areas where these tools are used, with the top three areas being schedule, cost, and procurement. Primavera-P6 and MSP are the two major tools in the area of schedule while SAP™ and internally developed tools are used for cost. SAP™, Smart Plant™, and internally developed software are used in the area of procurement for portfolio management. In all of the areas except schedule, organizations have tailored tools or developed custom-built software to be adjustable with their processes.

Firms use a combination of KPIs to track and measure the performance of their portfolios. The most common KPIs on dashboards are in the areas of cost and schedule. Change management is important for contractors as the third KPI and safety and cash flow for owners. The ideal dashboard should include at least three KPIs, cost, schedule, and safety.
The survey showed that even though portfolio management has been practiced in firms for more than 30 years, there are still some barriers such as standardization of processes, centralization of databases, prioritization systems, customization of dashboards, and generalization of concepts, justification of benefits to cost of implementation. Removing these barriers, which may be the subject of future research, can assist firms to improve the efficiency of their resources while pursuing their strategies.

Organizations do not have a systematic process to form their portfolios. They usually consider one or at most two criteria to rank their projects and then select them to form their portfolios. Even though multicriteria decision-making (MCDM) methods are available and many research reports and case studies have been published, these methods are not widespread within the industry to prioritize the projects. An efficient project portfolio formation process selects the most valuable projects considering limited budget.

The lack of a systematic approach in project portfolio formation was the main reason to develop a framework for the purpose of this dissertation. A balanced well-thought-out portfolio will have a great impact on achieving organization’s objectives. Indeed, the outcome of the survey showed that many portfolio managers were not comfortable with the lack of transparency and a consistent approach for project selection within their organizations. The proposed framework helps to form balanced portfolios in terms of risk, market, technology, product, and project type while considering the budget ceilings. This framework uses a hybrid of MCDM methods to prioritize the projects and to calculate the project’s risk factor. Chapter 3 explains in detail how the designed project portfolio
formation framework works by including organizational goals and strategic objectives in this framework.
Chapter 3: Project Portfolio Formation

3.1. Introduction

Organizations work hard to survive in the highly competitive business world. They are watching competitors in their business lines to figure out the future trends and take the right actions ahead of time. Moreover, they are always trying to be pioneers considering all the risks of their investments. Businesses are changing fast; therefore, organizations need to be agile enough to align themselves with new trends and stay ahead of competition. Organizations usually define their goals based on the market studies, and accordingly plan several possible strategies to achieve those goals.

In this chapter, a project portfolio formation framework is suggested to select the most valuable projects following the organizational strategic objectives. This framework helps to form balanced portfolios in terms of risk, project type, business line, and geographical location. Projects should be ranked within their portfolios before their selection. A set of preferred criteria plus a new risk factor are included in the project ranking process using a multicriteria decision-making method. A schematic of the framework is depicted in Figure 3.1.
The word “strategy” comes from a Greek term “strategos,” which means general. Strategy has two different definitions. Some authors defined the strategy as identifying end points and means to achieve them while others just focus on the means of achieving
goals rather than the end points (Weihrich, 1982). Andrews (1997) defined organizational strategy as a series of decisions that make the goals and objectives of an organization achievable. Mintzberg (1978) believed that strategy can be considered “a pattern in a stream of decisions.” Each strategy may include several related or unrelated projects that can create one or more portfolios. Organizations that repeatedly practice strategic decision-making can make better strategic decisions over time in comparison to those that observe the decision-making process of others (Cardella, 2012).

Strategic management includes: 1) Strategy formation, 2) strategy implementation, and 3) strategy control and evaluation (Hax and Majluf, 1995). Strategy implementation is more challenging in organizations in comparison to strategy formation (Meskendahl, 2010). One of the important steps in strategy implementation is program and/or project selection (Abbsianjahromi and Rajaie, 2012). The program and project selection process should include all the risks from the organizational level to the project level.

Aritua et al. (2009) considers portfolio management a way to implement organizational strategies and to respond to any changes in strategies. They suggested a model based on the literature review to connect organizational strategy to projects. Figure 3.2 illustrates that projects are the output of strategic objectives, which should be established before defining the projects. Strategic objectives are defined based on an organizational mission, which is the output of a vision. Therefore, organizations should clearly state their vision and mission before setting any strategic objectives (Aritua et al., 2009).
Most successful organizations have a continuous flow of projects in their dynamic portfolios for implementation of their strategies (Aritua et al., 2009; Cooper et al., 1997a).

Figure 3.3 schematically shows different possible strategies that an organization can take to achieve its goals by executing several hypothetical projects for each strategy. If projects 1, 4, 5, and 9 are selected to form a portfolio, strategy one is followed; several projects can be common among various strategies.
Portfolio formation is one of the most perplexing decision-making problems due to the number of parameters that affects a decision. Some of these parameters include (Cooper et al., 1997a):

- It deals with future with many uncertainties including threats and opportunities
- It should be done in a dynamic environment
- It is based on considering limited resources

Portfolios should be formed in an organization considering three major goals: 1) Maximize the share value, 2) create balance in terms of duration, risk, market, technology, product, and project type, and 3) meet the strategic objectives of the organization (Cooper et al., 1997a, 1997b).

At first, portfolio formation was used by financial investors who intended to buy stocks (Morkowitz, 1952, 1968). Selecting or forming the most beneficial portfolios based on organizational strategy to achieve defined goals was studied by several scholars in the
past 20 years (Abbasianjahromi and Rajaie, 2012; Yu et al., 2012; Carazo et al., 2010; Archer and Ghasemzadeh, 2004, 1999; Heidenberger and Stummer, 1999; Ghasemzadeh, 1998). Archer and Ghasemzadeh (2004, 1999, 1998) suggested a framework for portfolio selection, which considers resource restrictions. The stepwise framework as suggested can be modified according to the needs of organizations. It means that some of the steps can be eliminated if they are not practicable in an organization. Even though resource restriction is considered in the framework, the methodology does not give an explicit procedure to take into account restriction on resources, and the proposed framework is just a guideline for portfolio selection. Heidenberger and Stummer (1999) grouped the project portfolio selection models into five methods: 1) Mathematical programming approaches, 2) simulation and heuristics models, 3) cognitive emulation approaches, 4) real options, and 5) ad hoc. Carazo (2010) used a metaheuristic procedure based on a scatter search called “scatter search for project portfolio selection.” It is a multi-objective binary programming model that helps to obtain efficient portfolios aligned with organizational goals. Yu et al. (2012) used a generic algorithm based on a nonlinear integer programming approach to solve multicriteria project portfolio selection. It was shown that this method was a feasible and effective solution to multicriteria project portfolio selection. Abbasianjahromi and Rajaie (2012) suggested a framework for project portfolio formation in contractor organizations considering the bearable risk level of a contractor organization that can be influenced by several parameters such as:
• Execution capacity of an organization
• The number of existing projects
• Duration of existing projects
• The level of existing project portfolio risks in a contractor organization
• Financial capability of a contractor
• Human resource and equipment fleet of a contractor

The majority of the research in this area has been for research and development (R&D) project portfolio formation (Ghasemzadeh and Archer, 2000; Tian et al., 2005; Huang et al., 2008; Casault et al., 2013). Another negative point of the suggested portfolio formation processes is that they are complicated, and industries are not inclined to use them. The Construction Industry Institute (CII) research (CII RR303-3, expected 2015) highlights that lack of a systematic approach for project portfolio formation is an obstacle to portfolio management.

In this chapter, a portfolio formation process is described that can readily be understood by decision makers in infrastructure, building, heavy industrial, and light industrial sectors. This process can be used more effectively compared to existing methods because other processes were not prepared based on the needs of construction industries. The designed portfolio formation process considers restrictions on budget and other resources in organizations to select the projects that best align with strategic objectives to form the portfolios. The strategic objectives will be achieved by deciding the amount of budget that should be allocated in various portfolio hierarchy (Cooper et al., 1997b).
Some parts of this chapter are prepared based on the information gathered through the CII survey, interviews, and case studies (CII RR303-3, expected 2015).

3.2. Project Portfolio Formation Process

Portfolio formation process is the practice of selecting the most appropriate projects from a list of candidate projects and allocating them to diverse portfolio categories under budget ceilings to achieve organizational goals. Project selection includes using a decision-making method to prioritize the projects. There are many criteria to evaluate the candidate projects, so a multicriteria decision-making (MCDM) method should be used to prioritize them. The top rank projects have priority to be selected and included in portfolios.

Portfolio formation process has evolved over time. Vergara (1977) suggested the first portfolio formation process by evaluating the candidate projects one by one instead of pairwise comparison and adding the selected projects to ongoing portfolios. Abbasianjahromi and Rajaie (2012) highlighted that portfolio formation is important in both owner and contractor organizations.

Portfolio categorizations and project types vary among organizations. According to the CII RT-303 research findings, owner and contractor organizations have different approaches in categorizing their portfolios. Owners usually use geographical locations and then business lines to categorize their portfolios while contractors generally create their portfolios following their owners. Project types help individuals in an organization to better communicate with each other and monitor them in different phases (Crawford et
al., 2005). Project types can be productivity, maintenance, strategic, R&D, etc. Section 3.2.2 explains in detail portfolio categories and project types used in organizations. Considering previous research and the CII research on project portfolio management, the devised portfolio formation framework is shown in Figure 3.4.

The process of project portfolio formation begins with identifying the project types and portfolio categories available in an organization to create a portfolio hierarchy, deciding about the budget allocation to be top-down or bottom-up of the portfolio hierarchy, giving weights to different project types or portfolio categories for budget allocation, assigning candidate projects to their related project types and portfolio categories, prioritizing projects in each project type, creating balance in portfolios in terms of risks, considering the budget restriction on project types or portfolio categories to select projects, and eventually check interdependencies among selected projects. The selected projects will be assigned to their portfolios.

The project selection process compromises of four steps. The first three steps define the problem while the last one involves the selection of a MCDM method for ranking projects. The project selection process is within each project type because different types of projects may have different criteria to evaluate them. To avoid any bias in project prioritization, the homogenous evaluation of projects is required by comparing similar types of projects with one another. For example, all the productivity projects should be evaluated in one bucket while maintenance and Environmental, Health, And Safety (EHS) projects are in two autonomous buckets. Each bucket has its own specific set of preferred criteria.
An effective project portfolio formation framework needs to count for risks based on an organization perception of risks. It is crucial to include the risks at various organizational levels into the framework. In this dissertation, a new risk factor including all the risks at different organizational levels is introduced for each project. The risk factor may include different types of risks such as: financial and economic, industry, contract, organization, resource, and project risks.

Figure 3.4. Proposed Project Portfolio Formation Framework Process
The framework checks the interdependency among selected projects at the end. The selected projects should add value to an organization. For example, the preceding projects should be selected before the succeeding ones.

The portfolio formation has a dynamic nature because organizations are working in an environment where the relative importance of their strategies may keep changing (Houben et al., 1999). Some projects are ongoing while others are closing out, and new projects are coming to portfolios. The projects’ ranks and portfolio formation should be reviewed every six or 12 months according to the CII RR303-3 (expected 2015). Ranking of the projects illustrates which projects are more beneficial to an organization considering several preferred criteria. The projects’ ranks can possibly alter if the values of criteria change over time.

Table 3.1. Schematic Projects’ Ranks over their Life Cycles in a Portfolio

<table>
<thead>
<tr>
<th>Projects</th>
<th>½ Year</th>
<th>1 Year</th>
<th>1½ Year</th>
<th>2 Year</th>
<th>2½ Year</th>
<th>3 Year</th>
<th>3½ Year</th>
<th>4 Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₂</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₃</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₄</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₅</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>P₆</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₇</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>P₈</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>P₉</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
Table 3.1 indicates that the ranks of nine projects, $P_1$ to $P_9$, within a hypothetical portfolio are evaluated every six months. Figure 3.5 schematically illustrates projects’ ranks over a four-year period. The projects’ priorities vary due to business dynamics while new projects are added and some projects are closed out.

![Figure 3.5. Priority of Projects in a Hypothetical Portfolio](image)

### 3.2.1. Organizational Goals

One of the main purposes behind portfolio formation is to pursue the organizational goals effectively. Those candidate projects, which are aligned with organizational goals, are generally more profitable (if the company is a for-profit company). In owner organizations, stakeholders decide on the organizational goals. The type of organization (public or private) profoundly influences the defined goals while different industry sectors with the same organization type, private or public, tend to have similar goals.
The CII RT-303 research showed that private organizations are generally focused on increasing their profit over time. Private organizations try to achieve their goals using scarce resources, so portfolio formation is always an important phase of portfolio management to reach organizational goals. Large private organizations usually have several interrelated or completely autonomous projects in diverse business lines. Diversification strategy promotes the position of an organization in a business line and motivates the organization to enter into new markets (Abbasi et al., 2014; Veshosky, 1994; Markowitz, 1968). It gives the opportunity to an organization to keep a portfolio’s value high while decreasing the risk of organizational failure (Hummels, 2013).

Public organizations have a completely different approach in selecting their goals and objectives compared to private organizations. Safety and customers’ satisfaction are two high priority goals in public organizations. For example, in the CII interviews with many large organizations, one public organization in charge of school construction had adopted the strategy of avoiding any safety violations in the construction of school buildings. While focusing on safety, the total number of new seats at schools was also tracked to predict the level of future activities and increase public satisfaction.

### 3.2.2. Project Types and Portfolio Categories

The CII has divided up industries into four different sectors: infrastructure, building, light industry, and heavy industry. Different business lines in public or private organizations are included in each of these sectors, which have more or less similar project types. For example, the business lines in oil and gas industry are onshore and offshore at the top
level, and then the onshore breaks down to upstream and downstream. The upstream oil sector is also commonly known as the exploration and production (E&P) sector. The upstream business line includes underground crude oil and natural gas fields in various geographical locations. The downstream refers to oil refineries, petrochemicals, and the processing and purifying of raw natural gas. Different project types may be available to achieve organizational goals that make the portfolio formation a highly crucial task. For instance, manufacturing firms in the light industry sector own several types of projects such as grass-root (Greenfield) projects, new products, new technologies to increase production efficiency, upkeep of existing facilities, expansion of existing facilities, or a combination of these which create different possible project types. Other organizations in the heavy industry sector use the same project types. Projects are generally divided up into five different types in public and private organizations:

- Productivity projects: to lower utilities costs or decrease maintenance costs
- EHS projects
- Maintenance projects
- Strategic projects: increased sales/revenue
- R&D

Crawford et al. (2005) noted that some organizations have several portfolio categories but they don’t know that they are using portfolio categories within their organizations. Owner and contractor organizations categorize their projects and portfolios differently. Owner organizations usually group their projects based on their types or less common
based on their sizes while portfolio categories are arranged differently. A list of different portfolio categories in owner organizations suggested by the CII IR303-2 is listed below:

- Business line or industry
- Technology investment
- Product
- Funding source (usually in public agencies)
- Geographical location
- Environmental and safety
- Maintenance

A sample of portfolio categories hierarchy for an oil and gas organization is depicted in Figure 3.6. The business lines are at the top level and geographical locations are at the bottom level of the hierarchy. Each of the business lines is a portfolio category at the top level. The portfolio hierarchy is developed for the onshore business line; however, the offshore business line may include various types of platforms in different geographical locations. The upstream and downstream business lines are located under the onshore, and this organization does not have midstream business line related to storing, transporting and marketing of oil, natural gas, and natural gas liquids (NGL). The upstream includes the exploration and production in four different geographical locations: South America, North America, Europe, and the Middle East. The downstream comprises two business lines which are refineries and petrochemicals. Similar to upstream, four geographical locations are considered for refineries and petrochemicals.
The project types are only shown under the Middle East project portfolio while other geographical locations could have similar project types. The project types create the portfolio categories at the bottom level. This means that productivity projects similar to other project types make a portfolio category.

Contractors usually establish portfolio categories according to their business lines, clients, and geographical locations. They usually have business lines or clients at the top hierarchical level. Figures 3.7 and 3.8 indicate two sample portfolio categories in contractor organizations. Each of the business lines (bridge, highway, airport, and rail) is a portfolio at the top level and the clients (client 1, client 2, and client 3) are portfolios at the middle level. The locations (location 1, location 2, and location 3) are portfolios at the bottom level.
The highest ranked projects from different project types can be selected to form the portfolios by considering available resources. In this case, the selected projects are the best projects aligned with the preferred criteria decided by the decision makers.

### 3.2.3. Weights of Project Types or Portfolio Categories

The budget allocation for projects can be based on project type or portfolio category. A simple method to determine the budget allocation to project type or portfolio category is the use of weight factors. For example, if total amount of budget is $X$ dollars and there are four project types with 0.2, 0.4, 0.1, and 0.3 weight factors, then the amount of budget for each of these project types is 0.2$X$, 0.4$X$, 0.1$X$, and 0.3$X$ dollars respectively.
Most of the time weights will be selected by decision makers who are aware of organizational goals and strategies. Eckenrode (1965) has used the experts’ judgments to identify the reliability and time efficiency of six methods:

- Ranking
- Rating
- Partial paired comparison I
- Partial paired comparison II
- Complete paired comparisons
- Successive comparisons

These methods were used for three different situations including six various criteria. The methods were evaluated by the experts. The results showed when the number of experts increased from 6 to 30, the ranking method was more efficient compared to paired comparison methods (Eckenrode, 1965).

The budget allocation can be done using either a top-down or bottom-up procedure. If weights are given to portfolio categories and budget is allocated at the highest portfolio level, the budget allocation is top-down. For example, considering portfolio categories shown in Figure 3.6, if the budget is allocated to the portfolio categories, the amount of budget for each of the top portfolios will be identified; the budget breaks down to the lower levels of portfolio hierarchy where different project types are located. On the contrary, if weights are given to project types, the budget allocation can be calculated using a bottom-up procedure.
The average weights of project types for budget allocation in heavy industry are listed in Figure 3.9. The weights were identified based on the responses to a questionnaire from five major heavy industry organizations. Six questions were included in the questionnaire (Appendix 2) to identify how budget is allocated among low level portfolio categories. The low level portfolio is the same as project types. Moreover, the questionnaire asks about the weights of criteria for four project types that are presented in Section 3.2.5.2 (productivity; EHS; maintenance; and strategic). All the five organizations had the four suggested project types.

![Figure 3.9. The Average Weights for Four Project Types in the Heavy Industry](image)

The maximum weight is for the EHS projects; and strategic, maintenance, and productivity projects were ranked next, respectively. The weights are not required to be decimal as shown in Figure 3.9, which indicates the average weights in respondents’ organizations. Round numbers are usually selected for the weights of various project types to allocate their budgets. Considering the average weights of project types in Figure 3.9, organizations may consider weights of 5, 4, 3, and 3 for their EHS, strategic, maintenance,
and productivity projects, respectively. This means that organizations in the heavy industry have a common strategic objective to keep their facilities operating environmentally friendly and safely.

3.2.4. Assigning Candidate Projects to their Portfolio Categories

Resource limitations lead organizations to prioritize projects and choose the most profitable ones from the list of candidate projects. All the candidate projects or a subset of those will be selected for the next phase of the stage-gate process depending on the availability of resources. Project selection will be done during the feasibility study, which is included in gate-0. There are a total of seven gates in the CII front-end-planning: 1) Gate-0: feasibility, 2) gate-1: concept, 3) gate-2: detailed scope, 4) gate-3: design, 5) gate-4: construction, 6) gate-5: commissioning, and 7) gate-6: operation (CII IR213-2, 2014). The selected projects are better aligned with the strategic objectives to form the portfolios. For example, if the required budget for several candidate projects exceeds the budget ceiling, the most beneficial projects should be selected to form the portfolios. This highlights the importance of portfolio formation to achieve organizational goals.

A systematic approach is required to choose the most desirable projects based on preferred criteria and their weights. The criteria should be selected carefully by decision makers to cover all the important factors for achieving goals. Decision makers are usually selected from stakeholders to enrich the decision-making process. Selecting projects according to appropriate preferred criteria undoubtedly adds the highest value to the
organization. However, experts’ meetings and discussions are always useful in the process of portfolio formation for the enrichment of final decisions.

3.2.5. **Project Selection**

Project selection or ranking includes five steps: 1) Calculating a risk factor for each project, 2) identifying the preferred criteria, 3) assigning weights to different criteria, 4) deciding quantitative or qualitative values of criteria, and 5) using a MCDM method to rank projects.

The first step is to calculate a risk factor for candidate projects within each project type. The risk factor is calculated using analytical hierarchy process (AHP) based on qualitative evaluation of risks on the portfolio’s RBS. The next three steps define the problem and finally using a MCDM method to rank projects.

The preferred criteria should be identified in the second step. The projects and preferred criteria need to be best tied to the organizational goals. In addition, the criteria’s weights should be selected considering the strategic objectives. The values of criteria may be based on fact and figures, or they should be evaluated qualitatively. The final step is to choose a decision-making method to rank projects. The method can be as easy as a holistic method or as hard as a sophisticated mathematical model to rank projects. Having several alternatives with several quantitative or qualitative preferred criteria highlights the necessity of using a MCDM method to systematically rank projects and form portfolios. Moreover, the importance of using a MCDM method is that the alternatives can be compared with each other quantitatively and objectively rather than subjectively.
Alternatives are different possible choices available that can be evaluated using various criteria. All alternatives have values for each of the quantitative or qualitative criteria. The comprehensive CII survey illustrates that less than half of respondents use a sort of very simplistic prioritization method by comparing various alternatives using just one criterion in the finance and economic area such as net present value (NPV), internal rate of return (IRR), or ROI. Considering one criterion in the process of project prioritization does not cover all the aspects of decision-making problem. If projects’ risks are intended to be included in the project prioritization process besides one of the criterion in the finance and economic area, a MCDM method should be used to rank projects. The use of various criteria in one area is preferred because candidate projects may be from various business lines. The correlation varies among criteria in the same area, and this variation may be considerable when candidate projects are in different business lines.

3.2.5.1. Preferred Criteria

Evaluation of alternatives is usually based on several preferred criteria. These criteria belong to different areas such as finance and economic, political, EHS, geographical, and miscellaneous. Based on the CII RR303-3 (expected 2015), NPV, IRR, and return on investment (ROI) are typically used by the owner organizations to evaluate a variety of their alternatives. All these criteria are in the finance and economic area. The other preferred criterion for a manufacturing company is pioneer product, which is manufactured for the first time. Pioneer product belongs to the miscellaneous area.
Another criterion important to all organizations is safety to execute projects within their existing operating facilities.

NPV is the sum of incoming and outgoing cash over a period of time by considering the time value of money. It is used to determine the profitability of a project. In fact, a positive NPV results in a profit, while a negative NPV results in a loss. The formula to calculate NPV is: \[ \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} = 0 \], in which “t” is the time of cash flow, “i” is discount rate or rate of return, and “R_t” is the net cash flow at time t.

IRR is a rate of return that makes NPV of all cash flows equal to zero. Projects with high IRR are more desirable because they turn back the investment faster. IRR can be calculated using \[ \sum_{t=0}^{N} \frac{R_t}{(1+r)^t} = 0 \], which r is internal rate of return.

ROI is a profitability measure that shows the efficiency of a business. ROI is defined as net profit divided by investment cost. A high ROI means that a business profit is favorably high compared to investment cost.

Selecting qualitative and quantitative preferred criteria is one of the major steps in the process of project selection. Criteria can vary from one organization to another depending on the business lines and goals. Two different organizations which are in the same business line may have different preferred criteria for project selection process and forming their portfolios. More precise evaluation of criteria leads to more accurate project selection. The qualitative criteria can be converted to quantitative using the Likert scale with the optimal number of scales (Matell and Jacoby, 1972).

One of the advantages of forming portfolios based on project types is that preferred criteria to evaluate candidate projects are similar. Homogenous comparison of candidate
projects leads to selecting those projects that are more aligned with the goals of the organization. Four different project types are considered as five low level portfolios located at the bottom of the portfolio hierarchy (Figure 3.6). However, R&D projects can also be considered in one autonomous portfolio, the CII research (CII RR303-3, expected 2015) does not suggest any preferred criteria for them. Each project type has its own preferred criteria:

- **Productivity projects**
  - Payback period
  - NPV
  - IRR
  - Pioneer product
  - ROI

- **EHS projects**
  - Safety compliance
  - Safety risk
  - Amount of damage

- **Strategic projects**
  - Alignment to goals
  - NPV
  - IRR
  - Pioneer product
  - ROI

- **Maintenance projects**
  - NPV (based on failure cost history)
  - Criticality score
  - Safety risk

The preferred criteria can vary from one organization to another; however, the criteria mentioned above (or a subset of them) are among those that organizations usually
consider in prioritizing and selecting projects. The criteria identified above are the results of a two-year research effort sponsored by the CII (CII RR303-3, expected 2015).

The literature review showed that several criteria have been a focus of attention for project ranking and selection in different industries. United Nations Industrial Development Organization (UNIDO) suggested some criteria for benefit-cost analysis of projects in 1972. Those criteria are net present value (NPV), return on investment (ROI), payback period, and period to achieve the positive net flow.

Buchanan et al. (1999) suggested considering five criteria: 1) NPV, 2) strategic contribution of the projects, 3) risk of plant failure and damage due to natural disaster, 4) consequences of poor implementation of technology, and 5) environmental effects for the Electricity Corporation of New Zealand to rank capital and maintenance projects.

Nowak (2005) has considered four criteria: NPV, profitability index, probability of project success, and level of technology novelty to rank manufacturing and construction projects.

In transportation projects which are usually owned by public organizations, the criteria to evaluate projects are different. Some other criteria related to the decision-making problem besides the financial and the economic criteria were included in the decision-making problem. Ferrari (2003) defined six diverse criteria for ranking the transportation projects: 1) Congestion on the current urban highway, 2) congestion on the other urban roads in the metropolitan area, 3) congestion on the extra-urban roads in the metropolitan area, 4) cost of projects, 5) air pollution on the urban roads in the metropolitan area, and 6) land surface area that the project detracts from other, mainly agricultural uses.
Balali et al. (2010) suggested considering six different economic and technical criteria for selecting an appropriate structural system. These criteria were: 1) Cost-economic, 2) ease of construction-safety, 3) energy saving-environmental, 4) dead load-safety, 5) the number of stories-vulnerability to natural disaster, and 6) age and durability-safety.

Sadeghi and Ameli (2012) tried to optimize the allocation of energy subsidy among socio-economic subsectors in Iran. They considered six criteria to evaluate five various areas of industry, agriculture, commercial, transportation, and household. The preferred criteria are distribution of energy subsidy, energy intensity, air pollution cost, economic growth, inflation, and labor intensity. Except for the distribution of energy subsidy that is quantitative, other criteria are qualitative.

Gupta and Kumar (2012) defined some criteria to select an underground mining method. The criteria are grouped into two categories: 1) Intrinsic, and 2) extrinsic. The intrinsic criteria are “driven by nature or the surroundings and are uncontrollable.” The extrinsic criteria are “not directly associated with the deposit.” Eight criteria were defined in intrinsic category and five in extrinsic category. 13 criteria are selected to rank various underground mining methods. The following is the list of criteria:

- Dip (intrinsic)
- Shape of deposit (intrinsic)
- Thickness of ore body (intrinsic)
- Grade of ore (intrinsic)
- Capital investment (extrinsic)
- Strength of ore (intrinsic)
- Strength of host rock (intrinsic)
- Presence of surface features (intrinsic)
- Depth of the deposit (intrinsic)
- Dilution of extracted ore (extrinsic)
- Market (extrinsic)
- Labor skill (extrinsic)
- Health and safety (extrinsic)

The criteria in different areas that were explained above are summarized in Table 3.2 to better understand that preferred criteria are highly based on the decision-making area and organization. The knowledge and experience of experts should be used by organizations to figure out the list of preferred criteria for a decision-making problem. A list of criteria in various studies using different MCDM methods prior to 2006 is collected by Mendoza and Martins (2006).

Table 3.2. The Preferred Criteria for Projects in Various Areas/Organizations

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Area</th>
<th>Criteria</th>
</tr>
</thead>
</table>
| Buchanan et al. | 1999 | Electricity Corporation | • NPV  
|                 |      |               | • Strategic contribution of the projects  
|                 |      |               | • Risk of plant failure and damage due to natural disaster  
|                 |      |               | • Consequences of poor implementation of technology  
|                 |      |               | • Environmental effects  |
| Ferrari         | 2003 | Transportation | • Congestion on the current urban highway  
|                 |      |               | • Congestion on the other urban roads in the metropolitan area  
|                 |      |               | • Congestion on the extra-urban roads in the metropolitan area  
|                 |      |               | • Cost of projects  
|                 |      |               | • Air pollution on the urban roads in the metropolitan area  
|                 |      |               | • Land surface area that the project detracts from other, mainly agricultural uses |
Table 3.2. The Preferred Criteria for Projects in Various Areas/Organizations (Cont.)

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Area</th>
<th>Criteria</th>
</tr>
</thead>
</table>
| Nowak           | 2005 | Manufacturing and Construction | • NPV  
|                 |      |                             | • Profitability index  
|                 |      |                             | • Chances of project success  
|                 |      |                             | • Level of technology novelty |
| Balali et al.   | 2010 | Civil - Structural System  | • Cost-economic  
|                 |      |                             | • Ease of Construction-safety  
|                 |      |                             | • Energy saving-environmental  
|                 |      |                             | • Dead load-safety  
|                 |      |                             | • Number of stories-vulnerability to natural disaster  
|                 |      |                             | • Age and durability-safety |
| Sadeghi and Ameli | 2012 | Socio-economic              | • Distribution improvement of energy subsidy  
|                 |      |                             | • Energy intensity  
|                 |      |                             | • Cost of air pollution  
|                 |      |                             | • Economic growth  
|                 |      |                             | • Inflation  
|                 |      |                             | • Labor intensity |
| Gupta and Kumar | 2012 | Mining                     | • Dip  
|                 |      |                             | • Strength of ore  
|                 |      |                             | • Shape of deposit  
|                 |      |                             | • Strength of host rock  
|                 |      |                             | • Thickness of ore body  
|                 |      |                             | • Presence of surface features  
|                 |      |                             | • Grade of ore  
|                 |      |                             | • Depth of the deposit  
|                 |      |                             | • Capital investment  
|                 |      |                             | • Market  
|                 |      |                             | • Dilution of extracted ore  
|                 |      |                             | • Labor skill  
|                 |      |                             | • Health and safety |

It is apparent that each decision-making problem requires its own criteria. Considering all criteria in the process of decision-making is important to cover all the aspects of a problem. In this way, an alternative (project), which is best aligned with the criteria, will
be ranked higher. Even though some financial and economic criteria are globalized by UNIDO, the experts in an industry are the best individuals who can decide about preferred criteria.

The number of criteria in a decision-making problem can change the rank of alternatives. The correlation between criteria of different alternatives is not the same. This leads to have an alternative with different ranks changing the number of preferred criteria. For example, three criteria are used to rank several alternatives. If a fourth criterion is added to the list of preferred criteria, the alternatives’ rank varies due to various correlations between the fourth criterion and other criteria. This fact emphasizes the use of multiple preferred criteria instead of single criterion, which is very common in the industry.

3.2.5.2. Weights of Criteria

Preferred criteria do not have similar importance in different organizations. There are different ways to evaluate the importance of preferred criteria. The objective evaluation of criteria is possible by achieving consensus in a group of experts and giving a weight factor to each criterion. The experts achieve consensus using their knowledge and experience. The other method is that a group of experts evaluates quantitatively or qualitatively the weight of each criterion and then converts them to one quantitative value using analytical hierarchy process (AHP) (Kangas, 2006). In this method, each of the experts gives weights to criteria separately to be included in AHP. Another method to define the weight of each criterion is using the Delphi method, which is a group
brainstorming method that can be used to select an appropriate Likert scale to define the criteria’s weights (Loo, 2002; Gordon, 1994; Dalkey and Helmer, 1963).

In this dissertation, a questionnaire was distributed to the experts within the CII RT-303 members (Appendix 2). The scale of each question was 1 (most important) to 5 (least important) based on the CII definition. Five experts in heavy industry completed and returned the questionnaire. This helped to calculate the average weights of different criteria. The average criteria’s weights are depicted in Figure 3.10 based on the heavy industry respondents.

![Bar chart images](image)

**Figure 3.10. The Average Weights of Different Criteria for various Project Types**
Figure 3.10 indicates that payback period, safety compliance, criticality score, and alignment to goals have the highest weight among other criteria for productivity, EHS, maintenance, and strategic project types respectively.

The weights should be allocated to various criteria areas such as finance and economic, political, EHS, geographical, and miscellaneous. More than one criterion may belong to an area so to avoid giving higher weight to an area, the weights should be defined for the areas first. Criteria’s weights can be assigned by dividing the area’s weight among them. For example, if the finance and economic weight is 39% and this area contains three criteria (NPV, IIR, and ROI), then the weights of these criteria may be 17%, 11% and 11% respectively. In the case study given in Chapter 5, a method is described to convert the percentiles to integer numbers.

3.2.5.3. Project Selection Methods

The portfolio formation framework needs a MCDM method for ranking projects because the global evaluation of different project types from various business lines requires considering several criteria in different areas. Project selection using MCDM methods is not a new concept. It has been developed by many researchers for more than 40 years (Shakhsi-Niaei et al., 2011). A complete review of the MCDM applications is conducted by Kabir et al. (2013) for seven different methods in infrastructure industry sector. About half of the studies use a combination of those seven methods for selecting infrastructure projects. A reasonable and defensible project selection approach is important due to the following reasons (Iamratanakul et al., 2008):
• Project selection has impact on a wide range of practices such as product development, policy selection, etc.

• Project selection can be applied to project and technology selection because different technologies have different advantages and drawbacks.

• Project selection is always a puzzling concern for R&D departments that many researchers have already done research on various topics.

Some organizations use holistic approaches for project selection. A holistic approach where the desired alternative(s) are chosen without extensive analysis is sometimes the only method that can be used for project selection (Saaty, 1980). Organizations, which use holistic approaches, do not evaluate projects quantitatively based on preferred criteria; instead, projects are selected based on dominant policies. In fact, some projects are selected because they are politically and strategically important. In that case, other criteria will be eliminated because they are not dominant enough in comparison to political and strategic criteria that drive the decision-making process. For example, some oil and gas fields are common between two countries. Considering preferred criteria, extraction from these fields may not be beneficial; however, the political and strategic criteria force organizations to select these projects from the list of candidate projects. Therefore, they will be included without further assessment in a portfolio.

A rational and quantitative process for decision-making is essential for major complex decisions and to convince others (Golden et al., 1989). Different mathematical methods can be used for complicated decision-making problems. These methods are useful when
several alternatives and criteria are available to make the best decision. AHP (Saaty, 2012, 2008 and 1980), SMART (Chou and Chang, 2008; Barron and Barrett, 1996; Edwards and Barron, 1994), PROMETHEE (Mareschal et al., 1984; Brans, 1982), TOPSIS (Kelemenis et al., 2011), and ELECTRE (Almeida-Dias et al., 2012; Figueira et al., 2005; Roy, 1991) are common MCDM methods utilized in mathematical decision-making problems. The hierarchical breakdown of decision-making methods is shown in Figure 3.11. This hierarchy is designed based on research done by Fülöp (2005).

A classification of project selection methods in Figure 3.12 is proposed by Iamratanakul et al. (2008) based on the previous studies by Heidenberger and Stummer (1999) in the field of R&D project portfolio selection. The methods are categorized into six different core groups with wide varieties from “ad hoc” models to “benefit measurement” models. Some of these models have been used widely in different areas of industries because of their mathematical simplicity and availability of software. PROMETHEE and AHP are two
common methods for project ranking. They are included in “benefit measurement” core group, under “scoring” subgroup.

Figure 3.12. The Categorization of Project Selection Methods (Iamratanakul et al., 2008)

There is one main difference between the Fülöp’s decision-making hierarchy and Iamratanakul et al. categorization. Fülöp created the hierarchy based on the number of criteria and decision makers to solve a decision-making problem, while Iamratanakul et al. categorized based on various methods without considering the number of criteria and decision makers.
Some studies compared the effectiveness of using decision-making methods. All of these studies considered three to four criteria to compare different decision-making methods. The criteria in these studies are similar (Mendoza and Martins, 2006). Table 3.3 illustrates the criteria selected in four studies to compare different methods. For example, Gilliams et al. (2005) compares PROMETHEE II, ELECTRE III, and AHP methods for afforestation, which is the establishment of forests. They identify that PROMETHEE II is slightly preferable to the other two methods. Moreover, Mahmoud and Garcia (2000) compare weighted average (WA), PROMETHEE II, compromise programing (CP), ELECTRE II, and AHP to identify the best management alternative for anadromous fish migration through the Red Bluff diversion dam. They identified that WA is the best method. The comparison of decision-making methods shows that selecting the best method depends on its appropriateness for an organization and the consistency of results.

In this dissertation, PROMETHEE is suggested for project portfolio formation due to its flexibility in normalizing the difference between the values of projects for one criterion and the consistency of results. The availability of software, numerous applications, and manuals are other minor positive points of using this method. This method is explained in Chapter 4. A worksheet called Ex-PROMETHEE is designed for PROMETHEE I and II to have probabilistic analysis on input variables. The Ex-PROMETHEE should be used in conjunction with @Risk™.
Table 3.3. The Parameters to Compare Various Decision-Making Methods

<table>
<thead>
<tr>
<th>Reference</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gilliams et al., (2005)</td>
<td>• Ease of use</td>
</tr>
<tr>
<td></td>
<td>• Understanding the methods</td>
</tr>
<tr>
<td></td>
<td>• Variation in solutions in terms of results, changing criteria, and accuracy</td>
</tr>
<tr>
<td></td>
<td>• Implementation</td>
</tr>
<tr>
<td>Mahmoud and Garcia, (2000)</td>
<td>• Consistency of results</td>
</tr>
<tr>
<td></td>
<td>• Interaction with users</td>
</tr>
<tr>
<td></td>
<td>• Understanding the methods</td>
</tr>
<tr>
<td>Hobbs et al., (1992)</td>
<td>• Consistency of results</td>
</tr>
<tr>
<td></td>
<td>• Robustness of results by changing criteria</td>
</tr>
<tr>
<td></td>
<td>• Ease of computation</td>
</tr>
<tr>
<td>Duckstein et al., (1982)</td>
<td>• Ease of use of methods</td>
</tr>
<tr>
<td></td>
<td>• Confidence in results</td>
</tr>
<tr>
<td></td>
<td>• Assistance of methods to understand a problem</td>
</tr>
<tr>
<td></td>
<td>• Consistency of results with expectation of users</td>
</tr>
</tbody>
</table>

3.2.6. Resource Restrictions and Portfolio Formation

Portfolio formation is usually constrained by limited budget and other resource constraints. Budget can be allocated on the basis of project type or portfolio category. The amount of budget for each project type or portfolio category can be allocated by defining weights of project types or portfolio categories.

Each of the project types includes zero to several candidate projects with its own preferred criteria to rank the projects. The ranking of projects within a specific project type is complex because several criteria must be fulfilled. MCDM methods help to rank projects within each project type.

The highest ranking projects can be selected and allocated into their portfolios considering budget ceilings. These projects are those that better meet the preferred
criteria or better align with organizational goals. If weights are given to project types, the amount of budget for each category is known, and accordingly projects can be selected from the top ranked ones to achieve the budget ceiling of that project type. Those selected projects will be allocated to their related portfolios. On the other hand, if weights are given to the portfolio categories, the top ranked projects which are related to a portfolio category should be selected from different project types. The budget ceilings of portfolio categories should be considered when selecting the projects. The selected projects are those that better meet preferred criteria defined according to organizational goals. Having a process for portfolio formation is essential to select the most beneficial projects which can add the highest value to the organization using limited resources.

3.3. Risks in Project Portfolio Formation

3.3.1. Introduction

Organizations have to consider all types of risks within each of their businesses and, possibly, in the relationship between them. Risks should be considered at different levels of an organization. At the top managerial level, risks are part of an organization’s strategy and business model and can affect different portfolios, programs, and projects at lower managerial levels. These risks can have positive or negative effects on the organization depending on how well they are managed. Based on this fact, risk management at various managerial levels is an important process for organizations to survive. Figure 3.13 illustrates the two-way relationship of risks at various managerial levels.
Figure 3.13. Managerial Levels and their Interactions with Risks

Some risks at the top levels can be directly connected to two or three lower levels instead of one, and the opposite can also be true. For example, an organization makes a strategic decision to enter a new business and, accordingly, a huge amount of investment is required to construct a new plant. In this case, the strategic risks at the top level may transfer directly to this project located at the bottom level, and thus mismanaging the project could affect the strategy. The types of risks at different managerial levels of an organization and the strategies to manage these risks are illustrated in Figure 3.14. The risks at lower managerial hierarchy may have less impact on the overall organization.
Business model is a basic and simplified explanation of an organizational strategy (Casadesus-Masanell and Ricart, 2010; Flouris and Walker, 2005). An organization’s business model is a mechanism to achieve the goals considering major risks. Organizations should always consider all possible relevant strategies to achieve their goals. Strategy making is a time consuming activity (Clark, 2004) different from other management activities, because it is non-routine, non-programmable, unique, creative, vague, risky, and complicated compared to operational management that mainly cares about day to day activities (Harrison, 1999; Johnson et al., 2004). For example, strategic management is concerned with the size and location of manufacturing plants, the structure of service or telecommunication network, and the supply chain technology while operational management focuses on production scheduling and control, inventory management, quality control and inspection, traffic and materials handling, and equipment maintenance policies (MIT Sloan, 2015).
At the macro-level, the strategic decision-making should include all the risks of each strategy. A new strategy may be introduced with many uncertainties that make the process of strategy presentation highly complicated (Hendry et al., 2010). Several frameworks have been introduced for managing strategic risks (AIRMIC and IRM, 2002; Treasury, 2004; Secretariat, 2012). Considering strategic risks in the risk management process was not common during the first years of applying formal risk management. However, strategic risks have been considered and included in the process of risk management in the last 15 years. For example, Project Risk Analysis and Management (PRAM) Guide published by the Association of Project Management (APM) incorporates strategic risks in the risk management process (Simon et al., 1997; Chapman, 1997).

Risk management includes considering both the positive and the negative effects of an event. Most of the studies on risk management have focused on negative effects of risks or threats rather than positive events or opportunities (Zhang, 2007; Pellegrinelli et al., 2007, Jaafari, 2001). According to the Project Management Body of Knowledge (PMBOK), risk management includes “maximizing the probability and consequences of positive events and minimizing the probability and consequences of adverse events to project objectives” (PMI, 2013b). The Standard for Portfolio Management (PMI, 2013a) gives a similar definition for portfolio risk but at a higher organizational level as “an uncertain event, set of events, which if they occur, have one or more effects, either positive or negative, on at least one strategic business objective of the portfolio.” A follow-up definition of portfolio risk management is the “management of uncertain events and conditions as well as their interdependencies at the portfolio level that cause significant
positive or negative effects on at least one strategic business objective of the project portfolio and thus influence project portfolio success” (Teller and Kock, 2013). Portfolio risk management focuses more on achieving strategic objectives (Pellegrinelli, 1997; Lycett et al., 2004). Pellegrini (1997) summarizes the potential advantages of portfolio risk management as follows: 1) Greater visibility of projects for senior managers, 2) better prioritization of projects, 3) more efficient usage of resources, 4) better planning and coordination, and 5) explicit recognition and understanding of dependencies.

The risks of a project can affect a program, a portfolio, or even the strategy of the organization (CII IR303-2, 2014). A well-developed portfolio risk management process is required to prevent any negative effect on the performance of cost, schedule, quality, etc. Portfolio risk management in an organization is implemented to enhance four factors (Teller and Kock, 2013): 1) Transparency, 2) effects of ignoring risks, 3) capacity to cope with risks, and 4) extent of decision-making information. It helps to identify similar risks in multiple projects, the aggregation of which creates significantly more effects on the success or failure of a portfolio (CII IR303-2, 2014; Teller and Kock 2013). In fact, portfolio risk management gives higher and wider perspective to an organization compared to project risk management as shown in Figure 3.13. Moreover, portfolio risk management helps to avoid failure of the project portfolios and consequently increases success (Reyck et al., 2005).

A review of the risk management literature shows that project risk management is more developed than program and portfolio risk management (Sanchez et al., 2009; Teller and Kock, 2013), and its benefits have been widely recognized in literature (De Bakker et al.,
2011). Furthermore, a review of risk assessment procedures shows that these procedures are very similar from an organization to the next. PMBOK suggests a five-step process for project risk management (PMI, 2013b): 1) Strategy and planning, 2) identification, 3) analysis, 4) response, and 5) monitoring and control. On the other side, the Standard for Portfolio Management (PMI, 2013) suggested a four-step process for portfolio risk management including: 1) Portfolio risk identification, 2) portfolio risk analysis, 3) risk presentation, and 4) risk monitoring. These four steps include not only portfolio processes but also a risk management framework at any level (project or program). This standard introduces three categories which are structure, component, and overall risks. Structure risks are identified by considering the combination of projects in a portfolio. Component risks are at the project level that can be escalated to the portfolio level, and overall risks consider the interdependency among projects (Teller and Kock, 2013). Besides portfolio risk management process in the Standard for Portfolio Management, Teller and Kock (2013) suggest a five-step framework for portfolio risk management: 1) Identification of portfolio risks, 2) formalization of the risk management process, 3) prevention of risks, 4) observation and monitoring of risks, and 5) integration of project risk management in portfolio risk management.

Risks at different managerial levels can be integrated in a project management office (PMO) (Sanchez et al., 2009). Some risks are common among projects and/or programs. Integrating these risks helps to manage them more efficiently. For example, modularization of heavy equipment increases the safety of project site. The projects and programs costs can be reduced using one vendor due to the scale of business. In this way,
the integration reduces risk threats while increases risk opportunities. Some organizations do not believe in having the portfolio risk management in a PMO due to unclear benefit-cost analysis (Kutsch and Hall, 2009; Olsson, 2008); as a result, portfolio risk management is scarcely implemented in organizations (Reyck et al., 2005). This is not rational to avoid implementing portfolio risk management due to unclear benefit-cost analysis because risks have different impacts and probabilities. Identifying and mitigating some risks may compensate the cost of portfolio risk implementation much higher than ignoring those portfolio risks.

This chapter will not cover portfolio risk management process in great detail. Rather, it focuses on two major issues about portfolio risk management: first, how the risk management process can be used to create a balanced project portfolio in terms of risks; second, how portfolio risk can be estimated quantitatively to compare the risk of different portfolios in a dashboard.

The main purpose of this discussion is to create a balanced project portfolio based on qualitative analyses of project risks using AHP, and then to calculate a quantitative risk factor at the program and portfolio levels. This is important because a portfolio should be balanced in terms of not only risks but also business line, technology, product, and project type. Except for the risk, all the other parameters that have an influence on balancing a portfolio are considered in budget allocation for various portfolio categories (business lines, products, locations) and project types. For example, portfolios can be balanced in terms of business lines when an organization decides how the budget should be divided
up among various business lines. In the same way, organizations can create a balance in terms of products, locations, and project types.

Dashboards help to visually track the status of portfolios and to compare them to each other. Considering the survey results on project portfolio management explained in Chapter 2, survey participants expressed interest in having metrics relevant to portfolio risk reported in an ideal dashboard. In fact, portfolio risk was among the top areas to be included in an ideal dashboard. A risk factor is suggested to show the risk level of not only portfolios but also projects and programs. This risk factor can be included on dashboards to better track the risk level of different portfolios and their components.

3.3.2. Strategic Management

This section discusses strategic management and different tools that can be used to identify the risks at the strategy level. Strategic decision-making plays an important role in an organization’s survival. There are two ways to make strategic decisions: 1) learning-by-doing (LBD) and learning-by-observing (LBO) (Cardella, 2012), and 2) interactive and procedural. In the first way, the LBD can be improved by repeatedly making a decision. This helps to enhance the knowledge and skills of decision makers and eventually assists them to make better decisions over time. The LBO helps to increase the knowledge and skill of decision makers by observing others’ practices. The second way, which includes interactive and procedural strategic decision-making, is used in different situations (Hacklin and Wallnöfer, 2012). The interactive strategic decision-making is useful when organizational transition is happening or at the time of altering the available
strategies or creating new strategies. This procedure is applicable for the duplication of an organization. For example, the participatory decision-making is an interactive process in which the knowledge and the ideas of decision makers will be shared among all. Organizations based on one of these methods or a mixture of them establishes their strategic objectives that will be the foundation of project portfolio formation.

Strategy tools are helpful in creating integration and facilitating compromise among decision makers. These tools can be used in the two ways of strategic decision-making described above. Gunn and Williams (2007) defined the strategy tools as “concepts that assist strategic managers in making decisions” and “assist in providing a structure for analysis.” Clark (1997) described strategic tools as “concepts, analytical frameworks, techniques and methodologies” for use of strategic managers in decision-making. Strategic tools are methods to better define a complex situation and simplify it (Gunn and Williams, 2007). The majority of research on strategic tools is case studies on tools and less research has been done on how to use different tools.

Many strategic tools are available such as strength, weakness, opportunity, and threat (SWOT) analysis, critical success factors, Porter’s five forces, and value chain analysis are among strategy tools. Table 3.4 shows a list of strategic tools and their popularity based on a survey in 2007 among 149 UK organizations in different sectors of public, private, manufacturing, and service, and in different size of organizations small, medium and large. The SWOT, benchmarking, and critical success factors are among the top three tools used in strategic decision-making.
Table 3.4. Overall Usage of Strategic Tools (Gunn and Williams, 2007)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Tool/technique</th>
<th>Used (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SWOT</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>Benchmarking</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Critical success factors</td>
<td>51</td>
</tr>
<tr>
<td>4</td>
<td>Competitor analysis</td>
<td>38</td>
</tr>
<tr>
<td>5</td>
<td>Stakeholder analysis</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>Core competencies</td>
<td>32</td>
</tr>
<tr>
<td>7</td>
<td>Balanced scorecard</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>Scenario planning</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>Lifecycle analysis</td>
<td>23</td>
</tr>
<tr>
<td>9</td>
<td>Culture analysis</td>
<td>23</td>
</tr>
<tr>
<td>10</td>
<td>Stakeholder mapping</td>
<td>22</td>
</tr>
<tr>
<td>11</td>
<td>Value chain analysis</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>Resource capability analysis</td>
<td>15</td>
</tr>
<tr>
<td>13</td>
<td>Industry structural analysis (Porter’s 5 forces)</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>McKinsey 7 ‘S’ framework</td>
<td>11</td>
</tr>
</tbody>
</table>

Other research has been conducted the use of strategic tools in a strategy workshop (Hodgkinson et al., 2006). The SWOT is again the most common strategic tool in those workshops. Table 3.5 depicts the popularity of various tools in strategy workshops.

The SWOT was initially proposed and named TOWS by Weihrich (1982). He introduced this strategic planning methodology as “A Tool for Situational Analysis.” Organizations should identify and analyze their internal strengths and weaknesses while investigating their external opportunities and threats. Organizations have entirely different lists of internal and external crucial factors, and it is not possible to standardize these factors...
(Houben et al., 1999). Weihrich defined a nine steps process to formulate the strategy in an organization as shown in Figure 3.15.

Table 3.5. Analytical tools applied in the strategy workshop (Hodgkinson et al., 2006)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Tool/Technique</th>
<th>Used (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SWOT</td>
<td>62</td>
</tr>
<tr>
<td>2</td>
<td>Stakeholder Analysis</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>Scenario Planning</td>
<td>28.5</td>
</tr>
<tr>
<td>4</td>
<td>Market Segmentation</td>
<td>22.6</td>
</tr>
<tr>
<td>5</td>
<td>Competence Analysis</td>
<td>21.5</td>
</tr>
<tr>
<td>6</td>
<td>PEST(EL) Analysis</td>
<td>17.2</td>
</tr>
<tr>
<td>7</td>
<td>Value Chain Analysis</td>
<td>15.1</td>
</tr>
<tr>
<td>8</td>
<td>Other</td>
<td>12.5</td>
</tr>
<tr>
<td>9</td>
<td>BCG Matrix</td>
<td>8.6</td>
</tr>
<tr>
<td>10</td>
<td>Porter’s Five Forces</td>
<td>8.5</td>
</tr>
<tr>
<td>11</td>
<td>Cultural Web</td>
<td>5.5</td>
</tr>
<tr>
<td>12</td>
<td>McKinsey’s 7 S’s</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Figure 3.15. Strategic Planning Process (Weihrich, 1982)
All of the steps, which end in selecting the Alternative Strategies, have uncertainties. Risk analysis gives a better perspective of selecting a strategy. The organizational strategies may be concentrated in a business line, backward and forward integration, diversification, innovation, no change, international, firm’s image, etc. (Weihrich, 1982). For example, if the strategy is on business line, all project portfolios would be established to develop the business line. If the strategy is backward integration, an organization would buy all its vendors and suppliers or make agreements with them to decrease the risk of its business. The forward integration strategy is opposite.

The organizational strategy helps to identify the risks related to a business at the top level. These risks can be transferred to lower managerial levels (Figure 3.13). In this way, the portfolios, programs, and projects are formed considering the top level risks. The strategic tools are helpful to identify the top level risks.

3.3.3. Risks in Project Portfolio Formation

Risk management at the portfolio level is identifying and managing the opportunities and threats affecting multiple projects and programs simultaneously to achieve strategic objectives. The survival and advancement of an organization depend on selecting projects that create a high value portfolio while keeping a reasonable balance in the portfolio in terms of risk. The best portfolio does not necessarily include the top prioritized projects when a balance of projects should be created in terms of risks. Cooper et al. (1997) launched a survey with 35 leading organizations in various industries and concluded that
organizations conceptually create a balanced portfolio in terms of risks. A good project portfolio includes projects with a spectrum of risks. Selecting the top prioritized projects without looking at projects’ risks may form a high risk project portfolio, which increases the risk of total failure for an organization (Archer and Ghasemzadeh, 1999). Considering the risks for project portfolio formation should not be limited to project risks, but the risks at the higher managerial levels should also be included such as strategy, portfolio, and program risks.

Few research efforts have been conducted to include the level of projects’ risks in project portfolio formation. The most recent one is a proposed cross-entropy methodology, which is an innovative meta-heuristic method, to form a balanced R&D project portfolio (Abbassi et al., 2014). Furthermore, a framework is suggested to optimize project portfolio formation considering the bearable risk level of a contractor organization (Abbasianjahromi and Rajaie, 2012). This framework quantifies the risk endurable level of a company (RELC) using a MCDM method. The RELC is quantified considering six parameters in an organization: 1) Capacity in execution of various projects, 2) the number of existing projects, 3) duration of existing projects, 4) the level of project portfolio risk, 5) financial capability, and 6) resources. Those projects that minimize the difference between project portfolio risk and RELC will be included in portfolios. Moreover, Zeng et al. (2007) proposed a modified AHP to prioritize diverse risk factors in construction projects using fuzzy reasoning techniques.
Two methods of risk analysis, qualitative and quantitative, are available depending on the desired level of effort and available information. Hillson et al. (1996) suggested three ways to evaluate the level of risk for projects based on available information:

- Ordinal scale approach: risks will be evaluated qualitatively considering their impacts and probabilities.
- Cardinal scale approach: risks will be evaluated using a scale (e.g., from 1 to 9) for both their impacts and probabilities.
- Quantitative approach: risks will be evaluated using a quantitative value of their impacts and probabilities.

The first two methods of risk evaluation are qualitative methods. Being more specific, the second method evaluates risks qualitatively and converts them to quantitative value. The conversion happens by using a type of Likert scale. A quantitative risk factor is required to indicate an aggregation of risks of a project. The proposed method in this dissertation uses the risk breakdown structure (RBS) of a portfolio, which include similar project types. A project risk factor will be calculated based on qualitative evaluation of risks, and then aggregate the project risk factors to obtain a risk factor at program level, and finally propose a risk factor at portfolio level.

RBS organizes project risks into groups and sub-groups to provide a standard presentation of project risks in a hierarchy. The RBS is used to evaluate various risks for candidate projects in a portfolio and to calculate a project risk factor for balancing the level of risks in a portfolio. All the risks should be evaluated quantitatively by an expert group. In a
survey on risk analysis techniques, the use of expert judgment in organizations was identified as the most effective qualitative technique for risk analysis (Abbasianjahromi and Rajaie, 2012; Baker et al., 1998). This method is used in this dissertation in conjunction with AHP to convert the qualitative risk analysis into a quantitative risk factor for each project. Based on this approach, a 10-point Likert scale is used to convert the qualitative risk analysis to quantitative using the RBS of a portfolio for projects. The use of RBS in evaluating the risks of a project was suggested by Hillson et al. (2006) for a combination of qualitative and quantitative risks. Then, AHP is used to calculate a portfolio risk factor based on the project risk factors included in the portfolio. The weight of risks on the RBS should be identified before using AHP to calculate project risk factors. Different steps of calculating the portfolio risk factors are shown in a flowchart in Figure 3.16.

Another method of calculating risk factors is based on quantitative evaluation of risks using risk contingency values, which is the summation of multiplication of risks’ probabilities and their expected impacts. In each of the methods, the quantitative project risk factor is used to keep the balance in terms of risks in project portfolio formation because too many high risk projects in a portfolio makes an organization susceptible to loss in the future (Archer and Ghasemzadeh, 1999).

The benefit of using an RBS is that risks can be grouped within a portfolio (e.g., management, technical, financial, political, etc.) and assigned to a discipline (CII IR303-2, 2014).
3.3.3.1. Qualitative Risk Analysis

Some organizations use qualitative risk analysis in the process of project risk management. This method is useful when it is not possible to quantify risk impacts and their probabilities. Experts’ experience or existing databases are major resources for listing risks, evaluating them, and eventually finalizing the risk of each candidate project. The risk of projects in a portfolio should be evaluated based on a unique RBS for the portfolio. If the risks of projects are analyzed with various RBSs, the level of consistency
will decrease to evaluate the risk of candidate projects due to variation in the number of risks from project to project. Therefore, a similar RBS for one project type can be considered to evaluate the risk of candidate projects consistently.

In the proposed procedure in this dissertation, the qualitative evaluation of risks for each project should be converted to one quantitative risk factor when candidate projects are intended to form a portfolio. The projects and programs risk factors can be converted to a quantitative portfolio risk factor, which is useful for comparing various portfolios in an organization. AHP, a MCDM method, can be used to convert the qualitative evaluation of risks to a quantitative value for each candidate project. The RBS is created in the risk identification step. This can be used to form the hierarchy for AHP. This helps to calculate the quantitative value of each risk criterion for different projects. Moreover, various weights can be considered for different risk branches and their subsidiaries.

In the process of qualitative risk analysis, a quantitative risk factor can be calculated for each candidate project based on qualitative evaluation of risks on a similar RBS. Risk analysis at the project level should concentrate on project characteristics and objectives and put aside the strategic objectives of an organization (Sanchez et al., 2009); however, if the project objectives are not achieved, the strategic objectives will not be met. The hierarchy of risks in RBS can be used in AHP. Various candidate projects will be identified at the bottom of the hierarchy. The procedure to calculate a quantitative factor for each candidate project based on qualitative evaluation of risks in the RBS is described in the following steps:
Step 1: Create the RBS for one project type.

Step 2: Identify the weights of risk branch, risk sub-branch, risk sub-sub-branch, risk, etc. at different levels of the RBS (Figure 3.17).

Step 3: Evaluate all the risks qualitatively for various candidate projects using the Likert scale shown in Table 3.8.

Step 4: Use AHP to calculate the value of each risk for each project.

Step 5: Calculate the risk factor for each candidate project using the weights of various levels of hierarchy and the priority vectors.
Figure 3.17. A Sample RBS of a Project Type

An example of the sample RBS is shown in Figure 3.18.
3.3.3.1.1. Risk Identification

The first step in the process of calculating a quantitative risk factor based on qualitative evaluation of risks is creating the RBS. The RBS may be very complicated with several levels in different risk branches as shown in Figure 3.17. Tah et al. (1993) suggested a RBS for contractors as shown in Figure 3.18. The equivalent of Risk Branch, Risk Sub-branch, Risk Sub-sub-branch, Risk, etc. in Figure 3.17 can be matched with Figure 3.18. This conformity is demonstrated in Table 3.6.

Abbasianjahromi and Rajaie (2012) recognized that in the construction industry, the risk criteria are evaluated by experts. They surveyed the most common risk criteria and their weights in the construction industry. They identified 31 risk criteria at the portfolio level in six categories:

1. Financial and economic risks
2. Industry
3. Contract
4. Company (Organization)
5. Resource
6. Project risk

A suggested list of portfolio risks in various categories is available in Table 3.7. There are many common risks in the RBS in Figure 3.18 compared to the risks in Table 3.7, as suggested by Abbasianjahromi and Rajaie (2012).
Figure 3.18. A Proposed RBS for Contractors (Tah et al., 1993)
Table 3.6. Matching of Different Levels of Risk Hierarchy in Figure 3.17 with Figure 3.18

<table>
<thead>
<tr>
<th>Level in Figure 13.17</th>
<th>Match in Figure 13.18</th>
<th>Level in Figure 13.17</th>
<th>Match in Figure 13.18</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBS of Project</td>
<td>OVERALL PROJECT RISK</td>
<td>Risk 1141</td>
<td>availability</td>
</tr>
<tr>
<td>Risk Branch 1</td>
<td>INTERNAL RISK</td>
<td>Risk 1142</td>
<td>quality</td>
</tr>
<tr>
<td>Risk Branch 2</td>
<td>EXTERNAL RISK</td>
<td>Risk 1143</td>
<td>productivity</td>
</tr>
<tr>
<td>Risk Sub-branch 11</td>
<td>LOCAL RISK</td>
<td>Risk 1144</td>
<td>failure</td>
</tr>
<tr>
<td>Risk Sub-branch 12</td>
<td>GLOBAL RISK</td>
<td>Risk 1151</td>
<td>ground conditions</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 11</td>
<td>LABOR RISK</td>
<td>Risk 1152</td>
<td>accessibility</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 12</td>
<td>PLANT RISK</td>
<td>Risk 1153</td>
<td>type of work</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 13</td>
<td>MATERIAL RISK</td>
<td>Risk 1154</td>
<td>complexity of work</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 14</td>
<td>SUB-CONTRACTOR RISK</td>
<td>Risk 1211</td>
<td>management experience</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 15</td>
<td>SITE RISK</td>
<td>Risk 1212</td>
<td>availability of partners</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 121</td>
<td>PERFORMANCE RISK</td>
<td>Risk 1213</td>
<td>relationship with client</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 122</td>
<td>CONTRACTUAL RISK</td>
<td>Risk 1214</td>
<td>workload commitment</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 123</td>
<td>LOCATION RISK</td>
<td>Risk 1221</td>
<td>contract type</td>
</tr>
<tr>
<td>Risk Sub-sub-branch 124</td>
<td>FINANCIAL RISK</td>
<td>Risk 1222</td>
<td>contractual liabilities</td>
</tr>
<tr>
<td>Risk 1111</td>
<td>availability</td>
<td>Risk 1223</td>
<td>amendments to standard form</td>
</tr>
<tr>
<td>Risk 1112</td>
<td>quality</td>
<td>Risk 1231</td>
<td>head office</td>
</tr>
<tr>
<td>Risk 1113</td>
<td>productivity</td>
<td>Risk 1232</td>
<td>project</td>
</tr>
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<td>availability</td>
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<td>funding</td>
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<td>Risk 1122</td>
<td>suitability</td>
<td>Risk 1242</td>
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<td>productivity</td>
<td>Risk 1243</td>
<td>economic conditions</td>
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<td>Risk 1131</td>
<td>availability</td>
<td>Risk 21</td>
<td>inflation</td>
</tr>
<tr>
<td>Risk 1132</td>
<td>suitability</td>
<td>Risk 22</td>
<td>exchange rate fluctuation</td>
</tr>
<tr>
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<td>supply</td>
<td>Risk 23</td>
<td>technology change</td>
</tr>
<tr>
<td>Risk 1134</td>
<td>wastage</td>
<td>Risk 24</td>
<td>major client induced changes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Risk 25</td>
<td>politics</td>
</tr>
</tbody>
</table>
Table 3.7. Categorization and Risk Criteria (Abbasianjahromi and Rajaie, 2012)

<table>
<thead>
<tr>
<th>No.</th>
<th>Risk Criteria</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Interest rate</td>
<td>Financial and Economic Risk</td>
</tr>
<tr>
<td>2</td>
<td>Inflation rate</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Variation of petroleum price</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Dependency to special moneylenders</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Variation in government policies</td>
<td>Industry</td>
</tr>
<tr>
<td>6</td>
<td>Variation in production rate of principal materials</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>International limitation</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Variation in tariff</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Permission license</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Environmental rules</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Type of contract</td>
<td>Contract</td>
</tr>
<tr>
<td>12</td>
<td>Type of payment</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Low credibility of employer</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Low financial ability of employer</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Unfamiliarity of consultant to technical work</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Lack of cooperation history with consultant</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Ambiguity in contract documentations</td>
<td>Organization</td>
</tr>
<tr>
<td>18</td>
<td>Improper strategy in selection of region for work</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Improper strategy in doing especial type of projects</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Lack of enough experience of project management team</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Weak contractor relationship with employer organizations</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Lack of expert managers</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Lack of expert human resource</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Lack of professional sub-contractors</td>
<td>Resource</td>
</tr>
<tr>
<td>25</td>
<td>Shortage of equipment and machines</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Difficulty in supplying materials</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Design complexity</td>
<td>Project risk</td>
</tr>
<tr>
<td>28</td>
<td>Execution complexity</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Geographical and weather condition of project</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Force majors</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Unpredictable changes</td>
<td></td>
</tr>
</tbody>
</table>
3.3.3.1.2. **Weights of different Branches**

The second step is to define the weights for different levels of the RBS, which may be decided by an expert group. The weights will be used in AHP to calculate the quantitative risk factor for each project based on the qualitative evaluation of risks. At each level of the hierarchy, the sum of the weights should be equal to one. A sample weighting system is shown in Figure 3.19. For example, it is assumed that internal risks are twice as important as external risks. If risks are compared to each other at each level (Risk Branch, Risk Sub-branch, etc.), the elements of priority vector of pairwise comparison matrix could have been considered as weight factors. The priority vector calculations are explained in Chapter 4.

![Figure 3.19. A Sample of Weights for Different Branches on a RBS](image)

3.3.3.1.3. **Qualitative Evaluation of Risks**

The qualitative evaluation of risks for all candidate projects can be performed using the opinions of an expert group. The tool that can be used for qualitative evaluation of criteria is a 10-point Likert scale as shown in Table 3.8. The scale range is from 1 (Very low), which means a risk with very low impact and probability, to 10 (Extreme plus), which shows a
risk with maximum impact and probability. The impact and probability of criteria are considered by the experts based on their experiences, which is recommended in the literature (Abbasianjahromi and Rajaei, 2012; Baker et al., 1998).

Table 3.8. 10 Points Likert Scale for Risk Analysis

<table>
<thead>
<tr>
<th>Intensity of Risk</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very low</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
</tr>
<tr>
<td>4</td>
<td>Moderate plus</td>
</tr>
<tr>
<td>5</td>
<td>Strong</td>
</tr>
<tr>
<td>6</td>
<td>Strong plus</td>
</tr>
<tr>
<td>7</td>
<td>Very strong</td>
</tr>
<tr>
<td>8</td>
<td>Very, very strong</td>
</tr>
<tr>
<td>9</td>
<td>Extreme</td>
</tr>
<tr>
<td>10</td>
<td>Extreme plus</td>
</tr>
</tbody>
</table>

The qualitative risks of a sample of four candidate projects are evaluated and converted to quantitative values as shown in Figure 3.20. The hierarchy can be used in AHP while the criteria are at the top levels and the alternatives, candidate projects, are at the bottom of the hierarchy. The hierarchy is based on the simplified RBS, which was suggested by Tah et al. (1993).
The equivalent qualitative evaluation of 10 various risks is shown for each of the four projects. For example, the qualitative evaluation of CONTRACTUAL RISK is very strong (with a score of 7) for Project 4 and very low for Project 1 (with a score of 1).

### 3.3.3.1.4. Using AHP to Calculate Quantitative Risk Factors

AHP is explained in detail along with a sample example and a developed Matlab code in Appendix 4 and 5. The code can be modified for calculating the priority vector, $\lambda_{\text{max}}$, consistency index (CI), and consistency ratio (CR) of each of the risks for various projects.

The code is limited to cases when the hierarchy has maximum of three levels. More than
three levels in the hierarchy increases the complexity of using AHP and is not recommended. If the RBS is made of several levels, a part of the code can be used to calculate the priority vectors for each level and their $\lambda_{\text{max}}$, CIs, and CRs.

Two codes are developed to calculate the priority vector in two different cases. First, when the equivalent quantitative values for qualitative risks are available; second, when the quantitative pairwise comparison matrix that is equivalent to pairwise comparison of qualitative risks is available. For each of these cases, a code is developed.

The code in Section A3.1 of Appendix 3 is developed for the first case that can be used to calculate the priority vector, $\lambda_{\text{max}}$, CI, and CR based on the equivalent of qualitative risks.

The priority vector of each risk is calculated and shown in Table 3.9 using the code and equivalent qualitative risks given in Figure 3.20. The values of priority vector for high risk projects are high; for example, Project 2, 3, 1, and 4 have high risks for LABOUR RISK as shown in Figure 3.20. The values of a priority vector in Table 3.9 shows the level of risk for different projects.

<table>
<thead>
<tr>
<th>Project</th>
<th>LABOUR</th>
<th>PLANT</th>
<th>MATERIAL</th>
<th>PERFORMANCE</th>
<th>CONTRACTUAL</th>
<th>LOCATION</th>
<th>INFLATION</th>
<th>EXCHANGE</th>
<th>TECHNOLOGY</th>
<th>POLITICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project 1</td>
<td>0.136</td>
<td>0.133</td>
<td>0.400</td>
<td>0.190</td>
<td>0.063</td>
<td>0.417</td>
<td>0.133</td>
<td>0.200</td>
<td>0.167</td>
<td>0.143</td>
</tr>
<tr>
<td>Project 2</td>
<td>0.455</td>
<td>0.333</td>
<td>0.080</td>
<td>0.286</td>
<td>0.188</td>
<td>0.208</td>
<td>0.667</td>
<td>0.400</td>
<td>0.292</td>
<td>0.500</td>
</tr>
<tr>
<td>Project 3</td>
<td>0.364</td>
<td>0.067</td>
<td>0.320</td>
<td>0.143</td>
<td>0.313</td>
<td>0.083</td>
<td>0.133</td>
<td>0.080</td>
<td>0.417</td>
<td>0.071</td>
</tr>
<tr>
<td>Project 4</td>
<td>0.045</td>
<td>0.467</td>
<td>0.200</td>
<td>0.381</td>
<td>0.438</td>
<td>0.292</td>
<td>0.067</td>
<td>0.320</td>
<td>0.215</td>
<td>0.296</td>
</tr>
</tbody>
</table>

Table 3.9. The Priority Vector of Various Risks
The data entering in the code and the priority vector, $\lambda_{\text{max}}$, CI, and CR for LABOUR RISK is shown in Figure 3.21. CI and CR are always equal to zero when the pairwise comparison matrix is calculated based on the equivalent quantitative values of qualitative risks.

![Command Window](image)

Figure 3.21. Data Entering and Outputs of the Code for Quantitative Evaluation of LABOUR RISK

The second case is when instead of converting qualitative risks to quantitative values, the risks are compared to each other qualitatively to form this matrix. The equivalent of the qualitative pairwise comparison risk matrix can be calculated using the scales shown in Table 3.10.
The pairwise comparison of LABOUR RISK for candidate projects is shown in Table 3.11. This comparison follows the equivalent qualitative evaluation of risks in Figure 3.20. For example, the quantitative labor risk for Project 1, 2, 3, and 4 are 3, 10, 8, and 1. The first row of Table 3.11 indicates that Project 1 is neutral to itself, inverse strong to Project 2, inverse moderate to Project 3, and low to Project 4.
Table 3.10 can be used to convert the qualitative pairwise comparison of risks to quantitative values. The pairwise comparison risk matrix should be checked by calculating the values of CI and CR to make sure the evaluations are consistent. The code in Section A3.2 of Appendix 3 is used to calculate the priority vector, $\lambda_{\text{max}}$, CI, and CR for LABOUR RISK based on the information in Tables 3.10 and 3.11. The data entering and the output of the code are shown in Figure 3.22.
Risky candidate projects have higher risk factor value than low risk projects. CR is less than 0.1 and it shows that consistency is acceptable in the pairwise comparison of risks. It is obvious that the values of priority vector for each project in the first case are not equal to those in the second case; however, the severity of risk for the projects are similar in both cases.

Having the priority vectors, the risk factor for each candidate project can be calculated considering the hierarchy of weights (Figure 3.19) and priority vectors (Table 3.9) that are shown in Figure 3.23.

![Risk Hierarchy Diagram](image)

**Figure 3.23.** Weights of Risks and the Priority Vectors to Calculate Risk Factors
As an example, the risk factor for candidate project 1 is calculated below:

\[
RF_1 = 0.667 \times [0.667 \times (0.164 \times 0.136 + 0.539 \times 0.133 + 0.297 \times 0.400) + 0.333 \times (0.201 \times 0.190 + 0.118 \times 0.063 + 0.681 \times 0.417)] + 0.333 \times (0.157 \times 0.133 + 0.104 \times 0.200 + 0.229 \times 0.167 + 0.510 \times 0.143) = 0.219
\]

RF_2 = 0.329

RF_3 = 0.166

RF_4 = 0.287

Project 2 is the most risky project followed by Project 4, 1, and 3. This method helps to convert all the qualitative risks for a project to a single quantitative risk factor. The risk factor can be used in balancing a portfolio in terms of risks and in calculating a portfolio risk factor. These applications of risk factors are explained in the following sections.

### 3.3.3.2. Quantitative Risk Factor for Candidate Projects

Some organizations have created risk registers using their historical data and experts’ opinions. The process of project risk management, including the creation of risk register is described by Touran (2006) for owner organizations. The risk register includes the list of all risks including their probability of occurrences and their impacts. The summation of multiplication of risk probability and its impact is the expected value of all risks. The expected value depicts the severity of risks for each project. This expected value is called the degree of criticality of a project (Hillson et al., 2006). The risky projects have higher
risk factors. A sample risk register based on the RBS in Figure 3.19 and the values of risk impacts and probabilities is shown in Table 3.12 to calculate the total expected risk, which is the project’s risk factor.

Table 3.12. A Sample Risk Register and Related Risk Factor for a Project

<table>
<thead>
<tr>
<th>Risk / Opportunity</th>
<th>Risk Probability (%)</th>
<th>Risk Impact ($)</th>
<th>Expected Risk Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>LABOUR</td>
<td>20</td>
<td>1,200,000</td>
<td>240,000</td>
</tr>
<tr>
<td>PLANT</td>
<td>30</td>
<td>10,000,000</td>
<td>3,000,000</td>
</tr>
<tr>
<td>MATERIAL</td>
<td>60</td>
<td>5,000,000</td>
<td>3,000,000</td>
</tr>
<tr>
<td>PERFORMANCE</td>
<td>10</td>
<td>3,000,000</td>
<td>300,000</td>
</tr>
<tr>
<td>CONTRACTUAL</td>
<td>5</td>
<td>500,000</td>
<td>25,000</td>
</tr>
<tr>
<td>LOCATION</td>
<td>30</td>
<td>600,000</td>
<td>180,000</td>
</tr>
<tr>
<td>INFLATION</td>
<td>70</td>
<td>3,600,000</td>
<td>2,520,000</td>
</tr>
<tr>
<td>EXCHANGE</td>
<td>20</td>
<td>1,000,000</td>
<td>200,000</td>
</tr>
<tr>
<td>TECHNOLOGY</td>
<td>30</td>
<td>700,000</td>
<td>210,000</td>
</tr>
<tr>
<td>POLITICS</td>
<td>50</td>
<td>6,500,000</td>
<td>3,250,000</td>
</tr>
</tbody>
</table>

Total Expected Risk Impact (Degree of Criticality) | 12,925,000

The formula to calculate the degree of criticality is: \[ \sum_{i=1}^{n} \text{RP}_i \times \text{RI}_i \]  \hspace{1cm} (3.1)

\( n \): number of risks

\( \text{RP}_i \): risk probability for \( i^{th} \) risk

\( \text{RI}_i \): risk impact for \( i^{th} \) risk
3.3.3.3. Project Portfolio Risk Factor

Portfolio risk factor helps to compare the risk of various portfolios. There is no standard mathematical method to calculate the portfolio risk factor. It should be based on project and program risk factors. Two methods of calculating project risk factor were described in previous sections. For program j, the risk factor is:

\[
\text{Program j risk factor} = \frac{\sum_{i=1}^{n} \text{Cost of project}_{ij} \times \text{Risk factor of project}_{ij}}{C_{prj}}
\]  

(3.2)

\[
C_{prj} = \sum_{i=1}^{n} \text{Cost of project}_{ij}
\]  

(3.3)

\(n\): number of projects in a program

\(C_{prj}\): total cost of projects in program j

The program and portfolio risk factors cannot be calculated when the project risk factors are calculated with a combination of qualitative risks and quantitative risks. These two methods give risk factors in different scales and cannot be included together in calculating program risk factor. The portfolio risk factor can be calculated when all the project and program risk factors are available.

\[
\text{Portfolio k risk factor} = \frac{\sum_{i=1}^{n} \text{Cost of project}_{jk} \times \text{Risk factor of project}_{jk}}{C_{pok}} + \frac{\sum_{j=1}^{m} \text{Cost of program}_{jk} \times \text{Risk factor of program}_{jk}}{C_{pok}}
\]  

(3.4)
\[ C_{\text{po}k} = \sum_{i=1}^{n} \text{Cost of project}_{ik} + \sum_{j=1}^{n} \text{Cost of program}_{jk} \]  

(3.5)

\textbf{m}: number of programs in a portfolio

\textbf{C}_{\text{po}k}: total cost of projects and programs in portfolio \textit{k}

The proposed risk factors can be used to compare risk among projects, programs, or portfolios. High risk factors represent more risky projects, programs, or portfolios.

\textbf{3.3.3.4. Project Portfolio Formation Considering Risk}

A project portfolio must have a balanced mix of projects in terms of projects’ risks. In this dissertation, the calculated risk factor is considered as a criterion in the MCDM method to prioritize candidate projects. In addition to other important criteria, the risk factor is considered to optimize the rank of candidate projects more precisely.

An appropriate weight should be selected for the risk factor criterion in the MCDM method. The weight of risk factor should be selected by doing sensitivity analysis. Considering the intention of an organization to be risk-prone or risk-averse, the sensitivity analysis helps to identify the variations in projects’ ranks. This helps to select the most valuable projects while considering a limited budget. The sensitivity analysis on the weight of risk factor helps to select an appropriate weight for the risk factor considering the level of risk acceptance by an organization.
Chapter 5 includes a case study that describes project portfolio formation framework in an organization. It describes how the portfolios can be formed considering the risk factor in the project prioritization.

3.3.4. **Visualization of Portfolios’ Risk**

In the area of portfolio risk management, another issue identified in the comprehensive survey, reported in Chapter 2, is the inclusion of risk in a dashboard. Besides considering risks of projects and programs in the formation of a balanced project portfolio, organizations are interested to illustrate the level of portfolios’ risk using a quantitative index. Visualization of risk helps to easily identify high risk projects, programs, and portfolios by looking at a dashboard. A method is suggested in this section to calculate and demonstrate this index for the risk of projects, programs, and portfolios on a dashboard.

The risk matrix is used to show the risk of projects. It contains the risk impact versus the probability of impact of projects. Moreover, projects’ expected risk impacts (risk impact $\times$ probability of impact) with two other metrics may be visualized in a bubble graph (Cooper et al., 1997). This graph depicts risky projects with bigger circles while two other metrics such as cost, schedule, etc. are considered on the x- and y-axes.

The risk matrix can be used for programs and portfolios, besides projects. The modified impact and modified probability parameters for programs and portfolios help to visualize risk of projects, programs, and portfolios on a matrix. The modified impact is the expected cost overrun, and the modified probability is the probability of cost overrun.
Figure 3.24 shows a schematic risk matrix with modified probability, probability of exceeding cost overrun, on the x-axis and modified impact, difference of expected cost overrun and allocated budget ($\Delta$), on the y-axis. The boundaries of low, medium and high risk depends on the $\Delta$ values of projects, programs, and portfolios and the probability of exceeding cost overrun. Subtracting maximum and minimum values divided by two gives a rational boundary; however, the boundaries totally depend on organization strategy to be risk-prone or risk-averse. Risk-prone organizations can select a value higher than the average of maximum and minimum values, to set the low risk boundaries.

Assuming that projects’ costs have normal distribution, the expected cost overrun ($\bar{C}$) and $\Delta$ for each project can be calculated. If the output of the Monte-Carlo simulation shows that a project’s cost on 80 percentile is $60,000 using the Cumulative Distribution
Function (CDF), \( \bar{C} \) is $73,630 and \( \Delta \) is $13,630 with 9% probability of exceeding expected cost overrun.

The expected cost overrun is the project’s cost at the centroid of area under the CDF between the 80 and 99 percentiles. The formulas given in Table 3.13 can be used to calculate the expected cost overrun, \( \bar{C} \), for the allocated budget at various percentiles.

For example, the allocated budget is \( C_{50\%} \) at 50 percentile and \( \bar{C}_{50\%} = 0.7598 \sigma + \mu \). Knowing the value of \( \bar{C}_{50\%} \), the difference of expected cost overrun and allocated budget is \( \Delta_{50\%} = \bar{C}_{50\%} - C_{50\%} \). The probability of exceeding expected cost overrun is available alongside each formula.

Table 3.13. Formula for \( \bar{C} \) and \( \Delta \) at Various Probabilities of Allocated Budget

<table>
<thead>
<tr>
<th>Allocated Budget (C) @</th>
<th>Expected Cost Overrun (( \bar{C} ))</th>
<th>Difference of Expected Cost Overrun and Allocated Budget (( \Delta ))</th>
<th>Probability of Exceeding ( \bar{C} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>( \bar{C}_{10%} = 0.1672 \sigma + \mu )</td>
<td>( \Delta_{10%} = \bar{C}<em>{10%} - C</em>{10%} )</td>
<td>43%</td>
</tr>
<tr>
<td>20%</td>
<td>( \bar{C}_{20%} = 0.3207 \sigma + \mu )</td>
<td>( \Delta_{20%} = \bar{C}<em>{20%} - C</em>{20%} )</td>
<td>37%</td>
</tr>
<tr>
<td>30%</td>
<td>( \bar{C}_{30%} = 0.4653 \sigma + \mu )</td>
<td>( \Delta_{30%} = \bar{C}<em>{30%} - C</em>{30%} )</td>
<td>32%</td>
</tr>
<tr>
<td>40%</td>
<td>( \bar{C}_{40%} = 0.6097 \sigma + \mu )</td>
<td>( \Delta_{40%} = \bar{C}<em>{40%} - C</em>{40%} )</td>
<td>27%</td>
</tr>
<tr>
<td>50%</td>
<td>( \bar{C}_{50%} = 0.7598 \sigma + \mu )</td>
<td>( \Delta_{50%} = \bar{C}<em>{50%} - C</em>{50%} )</td>
<td>22%</td>
</tr>
<tr>
<td>60%</td>
<td>( \bar{C}_{60%} = 0.9222 \sigma + \mu )</td>
<td>( \Delta_{60%} = \bar{C}<em>{60%} - C</em>{60%} )</td>
<td>18%</td>
</tr>
<tr>
<td>70%</td>
<td>( \bar{C}_{70%} = 1.1070 \sigma + \mu )</td>
<td>( \Delta_{70%} = \bar{C}<em>{70%} - C</em>{70%} )</td>
<td>13%</td>
</tr>
<tr>
<td>80%</td>
<td>( \bar{C}_{80%} = 1.3332 \sigma + \mu )</td>
<td>( \Delta_{80%} = \bar{C}<em>{80%} - C</em>{80%} )</td>
<td>9%</td>
</tr>
<tr>
<td>90%</td>
<td>( \bar{C}_{90%} = 1.6539 \sigma + \mu )</td>
<td>( \Delta_{90%} = \bar{C}<em>{90%} - C</em>{90%} )</td>
<td>5%</td>
</tr>
</tbody>
</table>
The formulas in Table 3.13 can be used knowing the values of mean and standard deviation of each project. These values are calculable using the Monte-Carlo simulation outputs of each project.

The expected cost overrun is calculated assuming the probability of cost in excess of 99%, which is ignorable, because the cost of a project at 100% cannot be calculated mathematically on the CDF. The CDF is the output of Monte-Carlo simulation. Using expected cost overrun of projects, the risk index for programs and portfolios is:

\[ \text{Program j risk index} = \Delta \text{ of program } j \text{ @ a specific probability} \quad (3.6) \]

\[ \text{Portfolio k risk index} = \Delta \text{ of portfolio } k \text{ @ a specific probability} \quad (3.7) \]

The \( \Delta \) can be calculated using formula in Table 3.13. Cost of projects included in a program is assumed to have normal distributions. The mean and standard deviation of a program are:

\[ \text{Program j mean} = \sum_{i=1}^{n} \text{Mean of project } i \quad (3.8) \]

\[ \text{Program j standard deviation} = \sqrt{\sum_{i=1}^{n} (\text{Standard deviation of project } i)^2} \quad (3.9) \]

A similar concept can be used to calculate the mean and standard deviation of a portfolio. As an example, consider the portfolio hierarchy in Figure 3.25. Seven projects are in three programs that form two portfolios in addition to two single projects. It is assumed that all projects’ costs have normal distributions.
Figure 3.25. A Sample Portfolio Hierarchy to Calculate Risk at Different Levels

Table 3.14 indicates projects’ allocated budgets, means, standard deviations, and difference of expected cost overruns and allocated budgets ($\Delta$). The projects’ allocated budgets are assumed to be at 80% for all the projects. The last column on the right indicates the program number of each project.

<table>
<thead>
<tr>
<th>Project No.</th>
<th>Allocated Budget @ 80%</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$\Delta$</th>
<th>Program No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50,000,000</td>
<td>42,796,494</td>
<td>8,559,299</td>
<td>4,207,751</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>100,000</td>
<td>85,593</td>
<td>17,119</td>
<td>8,416</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>800,000</td>
<td>684,744</td>
<td>136,949</td>
<td>67,324</td>
<td>---</td>
</tr>
<tr>
<td>4</td>
<td>5,000,000</td>
<td>4,279,649</td>
<td>855,930</td>
<td>420,775</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>200,000</td>
<td>171,186</td>
<td>34,237</td>
<td>16,831</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>20,000,000</td>
<td>17,118,598</td>
<td>3,423,720</td>
<td>1,683,101</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>700,000</td>
<td>599,151</td>
<td>119,830</td>
<td>58,909</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>3,000,000</td>
<td>2,567,790</td>
<td>513,558</td>
<td>252,465</td>
<td>---</td>
</tr>
<tr>
<td>9</td>
<td>100,000,000</td>
<td>85,592,988</td>
<td>17,118,598</td>
<td>8,415,503</td>
<td>2</td>
</tr>
</tbody>
</table>
In Table 3.15, the values of $\sigma$ are assumed to be 20% of the mean values. The standard deviations can be calculated by having the Monte-Carlo simulation output. In this example, some hypothetical numbers are used without using the Monte-Carlo simulation, and that is the reason the values of $\sigma$ are assumed to be 20% of the mean values.

The $\Delta$ of programs can be calculated using the information given in Table 3.14. The mean and standard deviation of programs are calculated using formulas (3.8) and (3.9). Table 3.15 indicates the values of $\Delta$ of programs. The last column on the right indicates the number of portfolio of each program and project. Table 3.16 indicates the values of $\Delta$ for portfolios.

<table>
<thead>
<tr>
<th>Program No.</th>
<th>Program</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>Allocated Budget @ 80%</th>
<th>$\Delta$</th>
<th>Portfolio No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Program 1</td>
<td>42,882,087</td>
<td>8,559,316</td>
<td>50,085,607.40</td>
<td>4,207,759.72</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Program 2</td>
<td>86,363,325</td>
<td>17,119,051</td>
<td>100,770,718.67</td>
<td>8,415,725.61</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Program 3</td>
<td>21,398,247</td>
<td>3,529,089</td>
<td>24,368,328.61</td>
<td>1,734,900.31</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Project 3</td>
<td>684,744</td>
<td>136,949</td>
<td>800,000.00</td>
<td>67,324.02</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Portfolio No.</th>
<th>Portfolio</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>Allocated Budget @ 80%</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Portfolio 1</td>
<td>87,048,069</td>
<td>17,119,599</td>
<td>101,455,923.57</td>
<td>8,415,994.89</td>
</tr>
<tr>
<td>2</td>
<td>Portfolio 2</td>
<td>64,280,334</td>
<td>9,258,313</td>
<td>72,072,130.42</td>
<td>4,551,386.70</td>
</tr>
<tr>
<td>3</td>
<td>Project 8</td>
<td>2,567,790</td>
<td>513,558</td>
<td>3,000,000.00</td>
<td>252,465.08</td>
</tr>
</tbody>
</table>

Using $\Delta$ as the risk index, Figure 3.26 gives an overview of riskiness of projects, programs, and portfolios.
Figure 3.26. Comparative Risk Index of Projects, Programs, and Portfolios

Figure 3.26 helps to identify that Portfolio 1 is more risky than Portfolio 2. Program 2 contains three projects while Project 9 has the most influence on the risk index of this program.

3.4. Interdependencies in Project Portfolio Formation

3.4.1. Introduction

The other parameter that should be taken into account in project portfolio formation is the interdependencies among projects (Cooper et al., 1997a). The interdependency of projects in a portfolio is regarded as an important task that can be studied by researchers (Abbasianjahromi and Rajaie, 2012). A portfolio cannot include succeeding projects in the absence of their preceding projects. For example, if the product of Project A is the feed
of Project B, the construction of B before A does not benefit the organization. In fact, the construction of the succeeding Project B without A would waste organizational resources if providing feed for B from other resources was not considered in the economic analysis of B.

It is suggested that the interdependencies can be grouped into two categories: single interdependency and multi-interdependency. The single interdependency category includes two sub-categories: one-way and two-way. In one-way, one project needs to be constructed before another project, because the succeeding project needs the products of the preceding project. For example, in the construction of a refinery, the atmospheric unit produces the feed of the liquefied petroleum gas (LPG) unit; therefore, the atmospheric unit project precedes the LPG project. The construction of the LPG unit before the atmospheric unit would not create any value. In two-way, two projects need to be constructed simultaneously, because one or more products of each project will be the feed of another project and vice versa. For example, the atmospheric unit produces the feed of the vacuum unit, some of which will be sent back to the atmospheric unit. Consequently, these units should be selected to be constructed simultaneously.

The multi-interdependency includes three sub-categories: one-way, two-way, and a combination of the latter subcategories. The one-way includes several preceding and one succeeding projects. The two-way includes several projects in which the product of one project is the feed for another and the opposite. All of these projects should be constructed simultaneously to be able to commission them. The projects’ interdependency tree in a portfolio is shown in Figure 3.27.
3.4.2. Checking Interdependency in Project Portfolio Formation

The interdependency among projects should be checked after they are prioritized, balanced in terms of risks, and selected to form portfolios. The prioritization and balance of portfolios have already been explained in the previous sections of this chapter. The interdependency check may change the list of selected projects that were chosen based on their priorities and balanced in terms of risks in previous sections.

To finalize the list of selected projects, the proposed flowchart checks the interdependencies among projects in a portfolio. Figure 3.28 indicates a flowchart to check the projects’ interdependencies. The interconnecting arrows check the value that a project can add to an organization. In the one-way interdependency, those projects that...
precede other candidate projects should be selected first. In fact, preceding projects should be selected first followed by their succeeding projects. The two-way projects should be selected all together because selecting one project without other projects does not yield any products. The interdependencies check is included in the process of project portfolio formation in a way that the execution of the selected projects adds value to an organization.
Figure 3.28. Interdependency Check in Project Portfolio Formation

The flowchart can be used to computerize the interdependency check among projects in the project portfolio formation process.

Another way to consider the interdependencies among projects is to contemplate all the projects as a program, and the program is included in the framework. In this case, the
program will be treated as a project in the step of ranking projects. The preferred criteria should be calculated based on the collection of projects. This means that instead of calculating NPV, IRR, or other preferred criteria for each project autonomously, all the projects that have kind of interdependency with each other will be considered to calculate the preferred criteria. Therefore, the portfolio formation framework may rank a program high among other projects in order to select the program without any need to check the interdependencies.

3.5. Conclusions

A crucial process for the organizations’ success is an effective project portfolio formation process to create balanced portfolios with limited budget. This process is more crucial for the growth and success of large organizations with various business lines, project types, and geographical locations. These organizations need to have an established project selection process for including their projects in the appropriate portfolio. The project selection process needs a MCDM method due to the fact that several factors and criteria may have to be considered.

Portfolio categories and project types should be defined to assist organizations to better follow and achieve their goals. Organizations should allocate sufficient budgets to portfolio categories or project types to create balanced portfolios. Considering risks to form balanced portfolios in terms of risks is essential. The risks in the project portfolio formation should include all the risks related to a strategy, in addition to project risks.
Different decision-making methods are available to prioritize and select projects. The MCDM methods are applicable to select the most beneficial projects among candidate projects when there are several preferred criteria. PROMETHEE is the best MCDM method to rank candidate projects due to its flexibility in defining preference function for preferred criteria. Moreover, the project ranks are more consistent using PROMETHEE.

One of the important steps in portfolio formation process is defining input variables of project selection. Selecting the preferred criteria and giving appropriate weights to them have direct influence on the projects’ ranks. The criteria significantly vary from one business to another. Some of the more general and applicable criteria were introduced in this chapter to assist organizations in implementing systematic portfolio formation process within their organizations.

All possible preferred criteria should be considered in ranking projects. According to the survey from five heavy industry experts, most of the organizations use one or at most two criteria to rank their projects. The important point is that considering all the preferred criteria increases the accuracy of the prioritization because criteria have various correlations, which are not the same for different projects. Criteria may have different negative or positive correlations that vary from one project to another. This fact highlights the importance of considering as many preferred criteria as possible in the process of project ranking.

Risks are important in various phases of projects that an organization carries out. An integrated risk management is required to help organizations to achieve their strategic objectives. Project portfolio formation should be balanced in terms of risks. The suggested
process helps all organizations to calculate a risk factor for each project. Considering organizations’ risk-prone or risk-averse approach, they form their portfolios. The incorporation of the risk factor completes the project portfolio formation process including the project prioritization. This incorporation includes both qualitative and quantitative risk analysis.

The qualitative risk analysis can be converted to quantitative using a Likert scale and AHP. Using these tools, a risk factor can be calculated for each project. The risks can be grouped into low, medium, and high with equal intervals. In order to calculate the intervals, the low risk factor of the projects in a portfolio is subtracted from the high risk factor, and then divided by three. The prioritized projects located in these risk groups may be selected while considering the budget allocated to each risk group based on the risk-prone or risk-averse approach of an organization.

A visualized method is proposed to include the risk of projects, programs, and portfolios on a dashboard. The required parameters to visualize the risks on a dashboard are cost overrun and its probability. These parameters can be calculated using a Monte-Carlo simulation for each project.
Chapter 4: Multicriteria Decision-Making Methods for Ranking Projects and Calculating Risk Factors

4.1. Introduction

Decision-making methods should be selected based on the features of a decision-making problem. The number of criteria and decision makers are key factors in selecting a method. A multicriteria decision-making (MCDM) method is required if a problem includes several criteria. Most of the MCDM methods are subsidiaries of multi-attribute decision-making (MADM) methods.

Effective project portfolio formation is possible by optimizing the list of selected projects through identification of high value projects. Project ranking is one of the steps in the project portfolio formation framework (Figure 3.4). The fourth step in the project selection process is “Select a project selection method,” which could be one of the MCDM methods. PROMETHEE is used to rank candidate projects, and analytical hierarchy process (AHP) is used to calculate a risk factor based on qualitative evaluation of risks. The risk factor is one of the criteria to rank projects.

PROMETHEE is an effective and appropriate method to rank the projects because of two reasons. First, the preference functions in this method gives flexibility in defining how the
difference between criteria varies. In this method, the criteria can be normalized using six
different preference functions that better match with organizational goals. Second, the
projects’ ranks are more consistent by changing the number of criteria.
Ex-PROMETHEE is designed based on the PROMETHEE I and II to probabilistically analyze
projects’ ranks. This Excel worksheet based tool in conjunction with @Risk™ helps to
make probabilistic analysis on projects’ ranks. The probabilistic analysis is essential
because input variables have uncertainties, so in order to select projects with high
certainty, the probabilistic analysis of projects’ ranks is supportive.
AHP has been used widely in industries including the construction industry for ranking
different alternatives or identifying criteria’s weights. AHP is another method that will be
used in the case study described in Chapter 5. This method is compared to PROMETHEE
to illustrate the advantages of PROMETHEE to AHP for project portfolio formation.
Moreover, AHP is used to convert the projects’ qualitative risks to a quantitative risk
factor. A Matlab code is developed for AHP to avoid its numerous calculations.

4.2. Ex-PROMETHEE Tool for Probabilistic Analysis of Projects’ Ranks
PROMETHEE is one of the outranking methods under the MADM shown in Figure 4.1 that
is widely used in industry for various purposes. PROMETHEE stands for Preference
Ranking Organization METHod for the Enrichment of Evaluations.
Many qualitative or quantitative criteria are usually available in ranking and selecting the most favorable projects to form portfolios. In the process of portfolio formation, projects are the same as alternatives in MCDM methods. The intention is to select the most advantageous projects that better align with the goals based on the preferred criteria. 

PROMETHEE I and II are explained in detail in this chapter. An example is used to describe both the Visual PROMETHEE software and manual calculation to show how this method can be helpful in ranking alternatives. As part of this research, an Excel worksheet called Ex-PROMETHEE is developed for PROMETHEE I and II to be used in combination with @Risk® for probabilistic analysis of input variables and their effects on the ranking of alternatives.

### 4.2.1. History

PROMETHEE-GAIA, hereafter referred to as PROMETHEE, is one of the MCDM methods under the subcategory of outranking methods (Figure 4.1). PROMETHEE has been
evolving in the past 30 years. The applications of these methods have increased all over the world, especially used by scientists and managers to make decisions with high assurance and clarity. PROMETHEE includes six different methods (PROMETHEE I, II, III, IV, V, VI) which are useful for diverse purposes and complement each other. The GAIA is the graphical representations of the results. The Visual PROMETHEE software is developed to facilitate the use of these methods.

Roy (1968) defined an outranking relation as a binary relation $S$ on the set $Z$ of alternatives such that $z_1 S z_2$ if there are enough arguments to declare that $z_1$ is at least as good as $z_2$ (Bouyssou, 1996). There should be two conditions to declare that $z_1$ is at least as good as $z_2$:

- A majority of criteria advocates this assertion (concordance condition)
- A minority of criteria has not “too strong” opposition (non-discordance condition)

PROMETHEE originated at the European consultancy company SEMA and was presented by Roy in 1968 for the first time (Figueira et al., 2005). PROMETHEE (I and II) is the second outranking method introduced in 1982 (Brans and Mareschal, 2005) after ELimination and Choice Translating REality (ELECTRE) method. Major characteristics of PROMETHEE are ease of use, comprehensibility, and strength compared to ELECTRE. ELECTRE I, II, III, and IV methods have been used to solve some sophisticated problems before PROMETHEE was proposed. The weak point of the ELECTRE is that it requires many input parameters that their values should be identified by decision makers (Brans and Vincke, 1985).
Brans developed PROMETHEE I (partial ranking) and PROMETHEE II (complete ranking) in 1982 and presented them for the first time in a conference at the Université Laval, Québec, Canada (Brans and Mareschal, 2005; Brans, 1982). In 1984, PROMETHEE III (ranking based on intervals on a finite set of feasible solutions) and PROMETHEE IV (continuous case) were developed by Mareschal et al. Later, GAIA (Geometrical Analysis for Interactive Assistance) was proposed by Mareschal in 1988. PROMETHEE V (multicriteria decision aid-MCDA under constraints) and PROMETHEE VI (representation of the human brain) have been developed by Brans and Mareschal in 1992 and 1994, respectively. The main characteristics of PROMETHEE methods is shown in Table 4.1.

Table 4.1. Characteristics of Different PROMETHEE Methods

<table>
<thead>
<tr>
<th></th>
<th>PROMETHEE I</th>
<th>PROMETHEE II</th>
<th>PROMETHEE III</th>
<th>PROMETHEE IV</th>
<th>PROMETHEE V</th>
<th>PROMETHEE VI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Partial ranking</td>
<td>Complete ranking</td>
<td>Ranking based on intervals</td>
<td>Continuous case</td>
<td>MCDA under constraints</td>
<td>Sensitivity tool (Human Brain-HB)</td>
</tr>
</tbody>
</table>

Behzadian et al. (2010) studied different applications of PROMETHEE methods. Moreover the online bibliographical database available at http://biblio.promethee-gaia.net shows that these methods are amongst the most widely used MCDM methods in practice (Ben Amor and Mareschal, 2012). The applications of PROMETHEE methods have been increasing over the past 10 years. The maximum number of published papers in one year is 49 going back to 2011 while, from 2005 to 2011, there is an increasing trend in the
number of published papers as shown in Figure 4.2. The average number of papers in different publications from 1982 to 2003 is eight, but it has increased to 33 over the last 10 years. From 1982 to April 2014, 547 papers have reported the use of this method according to references available on the PROMETHEE-GAIA official website (http://promethee-gaia.net/biblio.html - Dec. 02, 2013).

![Figure 4.2. The Number of Published Papers Using the PROMETHEE-GAIA over more than 30 Years (http://biblio.promethee-gaia.net - Dec. 02, 2013)](image)

PROMETHEE has been applied in eight main areas and in a number of miscellaneous topics (Behzadian et al., 2010). More than 50% of publications are included in the top three areas. The eight main areas are listed below:

- Environmental Management
- Business and Financial Management
- Hydrology and Water Management
- Chemistry
• Logistics and Transportation
• Energy Management
• Manufacturing and Assembly
• Social
• Other topics: medicine, agriculture, education, design, government, sports

Several studies used PROMETHEE to rank alternatives in these areas (Brans et al., 1986; Al-Rashdan et al., 1999; Nowak, 2005; Buchholz et al., 2009; Halouani et al., 2009; Balali et al., 2010; Shakhsi-Niaei et al., 2011; Alencar and Almeida, 2011; Çalışkan, 2013; Çalışkan et al., 2013; Anojkumar et al., 2014). Moreover, several research were also focused on project selection (Brans et al., 1986 Al-Rashdan et al., 1999; Nowak, 2005; Halouani et al., 2009, and Balali et al., 2010). Therefore, PROMETHEE can be used in portfolio formation by selecting those projects that better align with business goals.

The Visual PROMETHEE software, which is downloadable on the PROMETHEE-GAIA official website (http://promethee-gaia.net/software.html) for all non-profit academic research, helps decision makers in the following areas (Mareschal, 2013):

• Evaluate several alternatives with several criteria for each
• Recognize the ideal decision according to preferred criteria
• Rank the alternatives from the best to the worst
• Create several scenarios for a problem and compare them
• Objectively justify decisions
• Visualize decisions to better understand the difficulty of making decisions
4.2.2. PROMETHEE Methodology

PROMETHEE methodology is explained in detail in Section A4.1 of Appendix 4. This methodology calculates a quantitative value for each alternative based on the normalized value of the difference between criteria of two alternatives. In fact, the alternatives are compared with each other by calculating a net outranking flow value ($\phi$), which is the difference between the positive outranking flow ($\phi^+$) and negative outranking flow ($\phi^-$). If $P_j$ is a preference function associated with $j^{th}$ criterion $f_j(\cdot)$, then:

$$P_j(a,b) = G_j[f_j(a) - f_j(b)] , \quad 0 \leq P_j(a,b) \leq 1 \quad (4.1)$$

In equation 4.1, $a$ and $b$ are two independent alternatives and $G_j$ is a non-decreasing function of deviation between $f_j(a)$ and $f_j(b)$. $G_j$ varies in the range of 0 to 1 based on type of preference function. Six preference functions are defined in PROMETHEE: 1) Level, 2) V-shape, 3) U-shape, 4) level, 5) linear, and 6) Gaussian (Figure A4.3 in Appendix 4). Knowing the value of $P_j(a,b)$ and weights of criteria, a preference index, $\pi(a,b)$, can be calculated using equation 4.2. The positive and negative outranking flows may be calculated using the preference index values, and consequently the net outranking flow (equation 4.12).

$$\left\{ \begin{array}{l} \pi(a,b) = \frac{\sum_{j=1}^{k} P_j(a,b) \cdot w_j}{\sum_{j=1}^{k} w_j} \\
\text{if} \quad \sum_{j=1}^{k} w_j = 1 \quad \rightarrow \quad \pi(a,b) = \sum_{j=1}^{k} P_j(a,b) \cdot w_j \end{array} \right. \quad (4.2)$$
\[ \phi^+(a) = \frac{1}{n-1} \cdot \sum_{x \in A} \pi(a, x) \]  
(4.3)

\[ \phi^-(a) = \frac{1}{n-1} \cdot \sum_{x \in A} \pi(x, a) \]  
(4.4)

\[ \phi(a) = \phi^+(a) - \phi^-(a) \]  
(4.5)

Alternatives can be ranked using the values of net outranking flow.

4.2.3. The Visual PROMETHEE Software Interface

The PROMETHEE software has evolved over the past 30 years. PromCalc and Decision Lab software were developed for PROMTHEE in 1990 and 2000 respectively (Mareschal, 2013). PromCalc was developed by Mareschal and Brans on MS-DOS. Decision Lab was a product of cooperation between Université Libre de Bruxelles and the Canadian company Visual Decision (Geldermann and Zhang, 2001). Mareschal started development of the Visual PROMETHEE in 2010 and increased the ease of use of the software in 2011 and 2012.

The Visual PROMETHEE software interface shown in Figure 4.3 has four sections. At the top, different criteria and their characteristics, such as unit and their groups, are defined. In the middle top section, the preferences for each criterion are selected. It includes three main items: Max/Min, Weight, and Preference Function which are described briefly in Table 4.2. These parameters give characteristics of each criterion. The characteristics are important in pairwise comparison of criteria for different alternatives. The remaining items in this section are related to the type of preference function selected. In the middle
bottom, statistics related to each criterion are shown according to the values of criteria for different alternatives. The quantitative or qualitative values of criteria for each alternative are listed in the bottom section.

Figure 4.3. The Visual PROMETHEE Software Interface
In Table 4.2, the Min/Max helps to define whether the minimum amount of criteria is favorable or the maximum. For example, if buying a car is the problem, the car with the lowest price is preferable when all other criteria are the same. If two cars with different powers but same other criteria are available, the one with more power will be selected.

The importance of criteria can be evaluated by defining their weights. The weights can be finalized through experts’ sessions that eventually reach a consensus.

The statistics section of the software interface (Figure 4.3) gives four statistical parameters for each criterion. The Minimum is the lowest value of alternatives for a specific criterion. The Maximum is the highest value of alternatives for each criterion, and the Average is the average arguments of a criterion including all alternatives, which is the summation of arguments for one criterion divided by the number of arguments. The standard deviation is calculated using the formula below, which its arguments are the entire population.

\[
\text{Population Standard Deviation of } j^{\text{th}} \text{ criterion} = \sqrt{\frac{\sum_{i=1}^{n} (f_j(i) - \mu_{f_j})^2}{n}} \tag{4.6}
\]

\(n\): the number of alternatives
4.2.4. PROMETHEE Example

One numerical example is available on the Visual PROMETHEE software (Zhang, 2013), which is identical to the example in the Visual PROMETHEE manual (Mareschal, 2013). Here another example is presented to show the use of the method. The objective is to select a new car from a list of four manufacturers. It is composed of the actual information gathered by the author from the car manufacturers’ websites.

The four manufacturers (n = 4) are Ford, Toyota, Honda, and Hyundai; the question is: which car meets your objectives best considering all the preferred criteria simultaneously? The first step as mentioned above is to collect the required information for all cars. The preferred criteria are price, rate of fuel consumption, power, guarantee period, trunk volume, and finance rate (k = 6).

Table 4.3 depicts the quantitative values of different criteria for all the alternatives. The information in Table 4.3 can be used to complete Table 4.4 if all the other required information is included for each criterion such as Min/Max, preference function, and weight.
Table 4.3. The Values of Criteria for Different Alternatives

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Price ($)</td>
<td>18,615</td>
<td>27</td>
<td>160</td>
<td>3</td>
<td>13.2</td>
<td>2.90</td>
</tr>
<tr>
<td>1 Ford Focus 4dr Sdn SE</td>
<td>Fuel Consumption (mpg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power (hp)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Guarantee Period (yrs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trunk Volume (ft³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Finance Rate (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Toyota Corolla 4dr Sdn SE</td>
<td></td>
<td>19,700</td>
<td>29</td>
<td>132</td>
<td>3</td>
<td>13</td>
<td>3.86</td>
</tr>
<tr>
<td>3 Honda Civic Sdn 4dr CVT LX</td>
<td></td>
<td>19,190</td>
<td>30</td>
<td>143</td>
<td>3</td>
<td>12.5</td>
<td>1.90</td>
</tr>
<tr>
<td>4 Hyundai Elantra 4dr Sdn Auto SE</td>
<td></td>
<td>18,200</td>
<td>28</td>
<td>145</td>
<td>5</td>
<td>14.8</td>
<td>3.90</td>
</tr>
</tbody>
</table>

The preference functions are all considered to have V-Shape with strict preference (p) above the maximum values of criteria (Figure 4.4). The values of p and the ideal criteria to be maximum or minimum are shown in Table 4.4. Using V-Shape preference function gives higher value to the largest criterion if the criterion is maximized and gives higher value to the lowest criterion if the criterion is minimized.

![V-Shape Preference Function]

Figure 4.4. V-Shape Preference Function for Minimum and Maximum Criteria in the Sample Example
The criteria are considered to have equal weights. This means $w_j = \frac{1}{6}$, $j = 1, 2, \ldots, 6$ as shown in Table 4.4.

### 4.2.4.1. Manual Calculations

The preference indices can be calculated using the criteria for all alternatives given in Table 4.4. The preference index matrix is used to calculate the positive and negative outranking flows illustrated in Figure 4.5.
One of the elements of preference index matrix is calculated explicitly:

\[
\pi(a, b) = \frac{1}{6} \cdot \left( G1[f1(a)-f1(b)] + G2[f2(a)-f2(b)] + G3[f3(a)-f3(b)] + G4[f4(a)-f4(b)] + G5[f5(a)-f5(b)] + G6[f6(a)-f6(b)] \right) = \frac{1}{6} \cdot \left( G1[18615-19700] + G2[27-29] + G3[160-132] + G4[3-3] + G5[13.2-13] + G6[2.9-3.86] \right) = \frac{1}{6} \cdot \left( \frac{-1085}{20000} + 0 + \frac{28}{170} + 0 + \frac{2}{15} + \frac{-0.96}{-5} \right) = 0.0707
\]
Therefore:

\[
\phi(a) = 0.0493 - 0.0424 = 0.0069 \quad \phi(b) = 0.0065 - 0.0827 = -0.0762
\]
\[
\phi(c) = 0.0684 - 0.0394 = 0.0290 \quad \phi(d) = 0.0831 - 0.0428 = 0.0403
\]

According to net flow values, the rank of cars according to the values of preferred criteria and the assumed preference functions are listed below.

1. d: Hyundai Elantra
2. c: Honda Civic
3. a: Ford Focus
4. b: Toyota Corolla

4.2.4.2. Software Results

The decision-making problem for selecting the best car is entered into the PROMETHEE software. Figure 4.6 depicts the information entered into the software for the sample example.
Figure 4.6. Sample Example Information Given to the Software

The values of positive and negative outranking flows, and consequently the net flows of all alternatives calculated manually, are exactly the same as the software output shown in Figure 4.7.

Figure 4.7. Rank of Alternatives Using Software
4.2.5. Ex-PROMETHEE for Probabilistic Analysis

Project ranking in the project portfolio formation framework includes many uncertainties related to input variables. The criteria’s values, criteria’s weights, and the boundaries of preference functions may have various probabilistic distributions. A tool is designed to give the capability of doing probabilistic analysis of input variables. This tool and its features are explained in this chapter.

The PROMETHEE software does not have the capability to consider probabilistic input variables such as criteria’s values, criteria’s weights, and the boundaries of preference functions. In order to include probabilistic analysis of criteria, their weights, and other input variables using PROMETHEE, an Excel spreadsheet which hereafter will be called Ex-PROMETHEE is developed based on PROMETHEE I and II to be used with @Risk® software. @Risk is an add-on software that works with Excel and allows Excel cells to be modeled according to various statistical distributions. The users can then conduct the Monte-Carlo simulation using the probabilistic input variables and obtain distributions of the outcomes. The combination of @Risk® software with Ex-PROMETHEE helps to make probabilistic evaluation of all the input variables in PROMETHEE. Ex-PROMETHEE has some limitations regarding the number of alternatives and criteria. It can accept up to 10 alternatives and 20 criteria.

The developed Excel worksheet has four spreadsheets: 1) Entry, 2) Net Flow, 3) Calculations (Calcs), and 4) Preference Function. The Entry spreadsheet is used for entering the required information for a decision-making problem. The Net Flow shows
the result of calculations for positive and negative outranking flow and net flow. The Calcs sheet includes all the detailed calculations to compute the net flow for each alternative such as: difference between criteria for two alternatives, the value of preference function for all alternatives according to the amount of differences between criteria, and preference index for all the alternatives. The Preference Function sheet includes the six preference functions in the PROMETEE. Buttons are offered on each spreadsheet to be able to move among them.

4.2.5.1. The Entry Spreadsheet

The Entry sheet of the designed Excel spreadsheet is shown in Figure 4.8. The light blue cells show the fixed cells, and the green cells show the entry cells. The upper part of the table is for entering different information for various criteria. C1, C2, …, and C20 on the top row are fixed cells that show the number of preferred criteria available in the decision-making problem. C1 means criterion number one and C20 shows criterion number 20. Other rows below the first row contain the criteria’s titles, units, ideal values, types, thresholds according to their types, and the last row in the criteria part of the table defines the weight of each criterion.

The lower part of the Entry table is for entering information related to alternatives. Alternative is a general term that can be used in all the decision-making problems. The alternatives in the project selection process are projects which should be ranked considering the input variables. Ex-PROMETHEE is designed to consider those alternatives in calculations that are defined with one of the terms a1, a2, …, a10 in front of them in
the first column of the Entry table. In fact, those alternatives will be considered in calculations that one of the terms a1, a2, ..., a10 is given to each alternative in column “B” of the Entry spreadsheet. For example, if there are six alternatives, then a1, a2, a3, a4, a5, and a6 must be given to different alternatives respectively. If these terms are not included in column “B,” that alternative will be excluded in implementation of PROMETHEE from the list of alternatives. In column “C,” the name of each alternative can be included in front of the terms a1, a2, ..., a10.

![Figure 4.8. Entry Sheet of PROMETHEE I and II in Ex-PEOMETHEE](image)

The Entry spreadsheet is designed for up to 10 alternatives and up to 20 criteria. The number of alternatives can be increased by modifying the Calcs and Net Flow.
spreadsheets. In the case study explained in Chapter 5, the highest number of alternatives is nine.

The weights of criteria should be entered differently in solving the decision-making problem with software, Ex-PROMETHEE, and manually. The sum of the weights should be equal to one in manual calculation while cardinal numbers are used in Ex-PROMETHEE and the software.

4.2.5.2. The Net flow Spreadsheet

The calculated net flows for all the alternatives are shown on this spreadsheet. Also, the positive and negative outranking flows of alternatives are illustrated on this page. Figure 4.9 is a snapshot of the Net Flow spreadsheet.

![Figure 4.9. The Net Flow Spreadsheet](image)

The table in this spreadsheet (Figure 4.9) is completely in light blue, which shows all the cells are fixed based on the information entered in the Entry spreadsheet. The detailed calculations are included in the Calcs spreadsheet, and the results of the detailed calculations are transferred to the Net Flow spreadsheet.
4.2.5.3. The Calcs Spreadsheet

All the required calculations to evaluate up to 10 alternatives considering up to 20 criteria are performed on this page. The net flow of each alternative and the outranking flows are calculated on this page and transferred to the Net Flow spreadsheet. Figure 4.10 indicates a snapshot of the Calcs spreadsheet.

![Calcs Spreadsheet](image)

Figure 4.10. The Calcs Spreadsheet

All the cells are light blue on this spreadsheet, and they are fixed. On the left side of the table shown in Figure 4.10, “a1” shows alternative 1 and (ai,aj) is comparison of alternative i and j for various criteria. The \( f_k(ai,aj) \) is the difference between the \( k^{th} \) criterion of alternatives i and j. The \( P_k(ai,aj) \) is the preference function for \( f_k(ai,aj) \).
4.2.5.4. The Preference Function Spreadsheet

There are six different preference functions that are shown on the Entry spreadsheet. All the preference functions are included on the Preference Function because the Greek numbers of each preference function should be used on the Entry spreadsheet. Figure 4.11 indicates the contents of this spreadsheet.

![Figure 4.11. The Preference Function Sheet](image)

4.2.5.5. Probabilistic Example with Ex-PROMETHEE

It is essential to analyze rank of alternatives when at least one input variable has a probabilistic distribution. The probabilistic analysis helps to make confident decisions. In
project selection (ranking), the input variables that may have probabilistic distributions are criteria’s values and weights.

The car example in Section 4.5, PROMETHEE Example, is used for probabilistic analysis. Two of the criteria have probabilistic distribution due to manufacturing uncertainties and operating conditions. These criteria are the rate of fuel consumption and power. A normal distribution is considered for these criteria with mean values equal to their given values and standard deviation (SD) equal to 10% of means. A sample of normal distribution for Honda’s power is shown in Figure 4.12.

![Image of normal distribution for Honda's power](image-url)

Figure 4.12. The Probabilistic Distribution for Honda’s Power
Using Ex-PROMETHEE in conjunction with @Risk, Figure 4.13 shows the cars’ net flow variation when the rates of fuel consumption and power have probabilistic distributions.

Eliminating the extreme values, the length of 25% to 75% boxplot overlap between two alternatives shows that their ranks possibly exchange. Hyundai and Honda are two close alternatives that their ranks may interchange. The possibility of rank exchange reduces for Honda and Ford. In addition, Toyota’s rank never changes because its boxplot, including the extreme bars, does not have any overlap with other alternatives.

If the criteria’s probabilistic distributions have higher standard deviations, the overlap between boxplots increases (Figure 4.14). This case makes the decision-making hard. In
this case, some other input variables such as criteria’s weights may be changed to identify the best alternative.

Figure 4.14. The Cars’ Net Flow Variation with Probabilistic Criteria (SD=50%.\mu)

The weights of criteria in previous figures are all equal. This is not an actual case because in reality the criteria’s importance varies from the decision maker’s view point. In this example, weights of 5, 4, 3, and 2 are considered for four criteria: price, rate of fuel consumption, power, and guarantee period. Figure 4.15 illustrates the net flow boxplots of four alternatives when there are two probabilistic criteria (SD=10%.\mu), which are the rate of fuel consumption and power.
Figure 4.15 indicates that the 25% to 75% boxplot overlap between Hyundai and Honda is ignorable compare to Figure 4.13. Honda and Ford have almost similar net flow boxplots, and Toyota’s rank may exchange with Honda and Ford in just extreme values. Honda has just a little higher net flow boxplot.

This probabilistic analysis helps to identify the best car among the four alternatives. A decision maker can select the Hyundai as the best choice with high assurance now. However, identifying the second ranked car needs more investigation by including more criteria in ranking cars such as interior quality, appearance, or popularity. These additional criteria are all qualitative that should be changed to quantitative using a Likert scale.
4.3. **AHP with Matlab Interface for Ranking Projects and Calculating Risk Factors**

AHP is one of the MCDM methods under the multi-attribute decision-making (MADM) category. AHP is one of the multi-attribute utility theory (MAUT) methods which is a subsidiary of the MADM as shown in Figure 4.16. The other method in the MAUT category is simple multi-attribute rating technique (SMART) developed by Edwards in 1977.

![Diagram showing the hierarchy of decision analysis methods](image)

*Figure 4.16. AHP in the Hierarchy of Decision Analysis Methods

In this chapter, AHP is described, and one example is used to show how manual calculations can be done. At the end, alternatives are ranked according to the value of criteria and their weights. In the portfolio formation framework, described in Chapter 3, this method can be used for project selection to evaluate several projects with multiple criteria. AHP is also intended to be compared with PROMETHEE in the process of portfolio formation.

A Matlab code is developed that is available in Appendix 5. The code has seven parts that are explained in Section 4.2.5.
4.3.1. History

Management science is committed to improving the techniques that facilitate and increase certainty for decision makers. They need to deal with decisions that organizations confront. Linear programming was the first technique developed and implemented in organizations to handle the difficulty of decision-making (Golden et al., 1989). Over time researchers used more sophisticated methods to deal with the complex industrial decision-making problems; one of these methods is AHP (Saaty, 2012).

AHP is a mathematically-based method invented by Saaty in 1970 for solving complicated problems. Saaty’s introduced AHP in 1980, and later he developed the method with Vargas and published improvements of the method in 1982.

AHP has wide applications in a variety of areas such as conflict analysis, operational research, portfolio selection, risk analysis, and other miscellaneous fields (Holguin-Veras, 1995; Golden et al., 1989). A list of references and their applicable areas prior to 2006 is given by Mendoza and Martins. Vargas (1990) studied the applications of AHP and categorized the research into four different categories: 1) Economic/Management, 2) political, 3) social, and 4) technological. Most recently, the same study on the applications of MAUT including AHP has been reviewed by Vaidya and Kumar in 2006. They categorized the AHP applications into six major groups:

1. Social
2. Personal
3. Education
4. Political
5. Manufacturing
6. Engineering
The majority of the AHP applications are for selecting the best alternative or ranking the alternatives in a variety of areas (Masoumi, 2015; Sabiruddin et al., 2014; Bijan et al., 2013; Borade et al., 2013; Sadeghi and Ameli, 2012; Saaty and Shang, 2011; Başaran et al., 2010; Pirdashti et al., 2009; Saaty, 2007). The prioritization of expenditure and allocation of scarce resources is always an important problem in corporations and governments considering diverse economic, social, political, environmental, cultural, and other criteria. Saaty (2007) suggested a method for dealing with multiple decisions for prioritizing bills in the U.S. Congress using AHP. Pirdashti et al. (2009) used AHP and other MCDM methods using both tangible and intangible criteria to select the best R&D projects in the chemical industry. Başaran et al. (2010) used AHP to select a desalination plant among four alternatives and seven preferred criteria. R&D project selection is vital in organizations to get competitive advantages in the challenging business world.

Saaty and Shang (2011) proposed an innovative AHP to capture the relationship between different levels of activities contributed by people to society. It is an extension of AHP to include a system with heterogeneous elements. Sadeghi and Ameli (2012) used AHP to allocate the energy subsidy among socio-economic subsectors in Iran. They considered six criteria including one qualitative criterion to prioritize five different areas (alternatives) which are industry, agriculture, commercial, transportation, and household. Recently, Borade (2013) has used AHP to adopt a vendor-managed inventory (VMI) practice which is essential in the collaborative supply-chain management. Bijan et al. (2013) compared the user satisfaction of e-commerce websites by AHP. Finally,
Sabiruddin et al. (2014) chose appropriate process parameters to obtain the desired weld quality for gas metal arc welding of medium carbon steel specimens using AHP.

The philosophy and methodology of AHP have been explained with examples in several books and articles (Masoumi, 2015; Bijan, 2013; Başaran et al., 2010; Saaty, 2008, 2005, 2004, 2003, 1994a, 1994b, 1990, 1980; Saaty and Vargas, 1982; Holguin-Veras, 1995; Golden et al., 1989). AHP is one of the most widespread MCDM methods because of its simplicity and the availability of several software packages that can be used for its implementation such as Expert Choice®.

AHP has been used most recently in the construction industries for various objectives like project selection (Yazdani-Chamzini et al., 2013; Fouladgar et al., 2012; Ebrahimnejad et al., 2012), contractor selection (Cheng et al., 2012), procurement method or project delivery selection (Wang et al., 2013), supplier selection (Eshtehardian et al., 2013), compression of project schedule (Moselhi and Roofigari-Esfahan, 2012), technology selection (Gupta and Kumar, 2012), risk analysis (Wang and Li, 2013; Zhang, 2012; Shi, 2012; Subramanyan et al., 2012), reliability of asphalt pavement (Rui et al., 2014), success factors identification (Kog and Loh, 2011), safety (Zhao, 2013; Yu and Liu, 2012), and maintenance (Salem et al., 2013; Wakchaure and Jha, 2012).

### 4.3.2. What does the Analytical Hierarchy Process Mean?

There is a philosophy behind each word of “Analytical Hierarchy Process” (AHP) that precisely describes this method (Golden et al., 1989). Analytic stands for using numbers and mathematical reasoning and also intuition. Hierarchy is the way that a decision-
making problem is decomposed. A hierarchy is made of goals at the top level and then criteria, sub-criteria, and finally alternatives at the lower levels. AHP can have many levels, and when the number of levels increases, it makes the decision-making problem more complicated. A schematic view of a three levels hierarchy is shown in Figure 4.17.

![Three Levels of Hierarchy](image)

The process describes the complexity of the decision-making. The important decisions cannot be made in one meeting. It is necessary to think about a decision, gather required information, and negotiate the results in a group if required. Therefore, process includes learning, debating, and revising the priorities.

### 4.3.3. AHP Methodology

AHP methodology is explained in detail in Section 4.2 of Appendix 4. The methodology is based on calculating a pairwise comparison matrix. This matrix can be calculated using the values of criteria for various alternatives. If there are “n” alternatives and “m” criteria,
$w_i$ indicates the value of $k^{th}$ criterion for $i^{th}$ alternative. Then element $a_{ij}$ of the pairwise comparison matrix $A^k$ can be calculated:

$$a_{ij}^k = \frac{w_{ki}}{w_{kj}}$$  \hspace{1cm} (4.7)

$$A^k = \begin{bmatrix}
1 & a_{12}^k & \cdots & a_{1n}^k \\
\frac{1}{a_{12}^k} & 1 & \cdots & a_{2n}^k \\
\vdots & \vdots & \ddots & \vdots \\
\frac{1}{a_{1n}^k} & \frac{1}{a_{2n}^k} & \cdots & 1
\end{bmatrix}$$  \hspace{1cm} (4.8)

AHP allows inconsistency on input variables such as criteria’s weights due to using experts’ judgments. Consistency ratio (CR) should essentially be checked when one criterion is evaluated based on experts’ judgments rather than objective measurements. Calculating $A^k$ based on the real values of criteria give a pairwise comparison matrix with zero consistency index (CI) and zero CR. Otherwise, the CI of the pairwise comparison matrix should be checked using the procedure explained in Section A4.2 of Appendix 4.

The priority vector (PV) of each criterion should be calculated to measure the quantitative values of alternatives. The $PV_p^k$ is the $p^{th}$ element ($p^{th}$ alternative) of $k^{th}$ criterion and $n^{th}$ alternative:

$$PV_p^k = \frac{\sum_{i=1}^{n} \frac{w_{ki}}{w_{kj}}}{n}, \hspace{1cm} (k = 1, \ldots, m \hspace{0.5cm} \text{and} \hspace{0.5cm} p = 1, \ldots n)$$  \hspace{1cm} (4.9)
A similar procedure can be used to calculate the priority vector of the criteria (PV_c). The value of the th alternative is:

\[ \sum_{k=1}^{m} PV_{C_k} \cdot PV_i^k \]  

(4.10)

Comparing these values, the rank of each alternative would be identified. The car example is solved in Appendix 4 to illustrate the procedure of manual calculations.

4.3.4. AHP Code Using Matlab

AHP has numerous calculations depending on the number of alternatives and criteria. Several free Excel spreadsheets are available online that can be used for AHP; none of the previous research has used Matlab software to develop an AHP code. In this dissertation, a Matlab code is developed for AHP to avoid manual calculations (Appendix 5). Matlab helps to have a flexible AHP code that can be completed in the future by adding the capability of having probabilistic analysis of input variables. Matlab code can be used like an interactive tool. The code can be designed in a way that asks the required inputs and gives the relevant outputs. All input variables should be entered in Matlab to use AHP. The required input variables in the code are listed below:

- Number of alternatives
- Number of criteria
- The value of each criteria for all alternatives
- The pairwise comparison matrix of criteria
The ideal value of each criterion to be maximum or minimum

The outputs of the AHP code are the following items:

- The maximum eigenvalue for different pairwise comparison matrices
- The confidence interval for different pairwise comparison matrices
- The confidence ratio for different pairwise comparison matrices
- Priority vector for different pairwise comparison matrices
- The value of each alternative

The developed code in Appendix 5 can be run in format of *.mat file in Matlab software.

The code includes seven parts that are explained in detail in the next section.

4.3.4.1. How Does the Matlab Code Work?

The code in Appendix 5 has seven different parts, which each will be explained in detail.

Input variables are entered in parts 1, 2, and 4. Other parts of the code are for the required calculations in AHP. Figure 4.18 illustrates different parts of the code in one view.

The following sections describe each part of the code using the car example.
4.3.4.1.1. Part 1

The following input variables are needed in part 1:

- Number of projects (n)
- Number of criteria (m)
- All the elements of matrix “A”

Elements of matrix “A” include the value of criteria for all projects. The code asks the elements of matrix “A” by showing the row number (i) and column number (j) of each
element. The \((i,j)\) is an element of matrix “A” for \(i^{th}\) project and \(j^{th}\) criterion. The code asks the user to enter the values of one criterion for all projects, and then it asks about the values of other criteria. This means that the elements of matrix “A” will be entered column by column.

An example used for PROMETHEE in Section 4.1.5 is practiced with the Matlab code. Table 4.5 indicates required information in the car selection example. Figure 4.19 shows a portion of the information that should be entered into the code. The information refers to the number of alternatives, which is four, and the number of criteria, which is six. Finally, matrix “A” will appear on the screen including the values of all criteria for various alternatives (Figure 4.20).

### Table 4.5. Quantitative Values of Criteria for the Example

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Price ($)</td>
<td>Fuel Consumption (mpg)</td>
<td>Power (hp)</td>
<td>Guarantee Period (yrs)</td>
<td>Trunk Volume (ft³)</td>
<td>Finance Rate (%)</td>
</tr>
<tr>
<td><strong>Ideal Alternatives</strong></td>
<td>Min.</td>
<td>Max.</td>
<td>Max.</td>
<td>Max.</td>
<td>Max.</td>
<td>Min.</td>
</tr>
<tr>
<td>1 Ford Focus 4dr Sdn SE</td>
<td>18,615</td>
<td>27</td>
<td>160</td>
<td>3</td>
<td>13.2</td>
<td>2.90</td>
</tr>
<tr>
<td>2 Toyota Corolla 4dr Sdn Plus SE</td>
<td>19,700</td>
<td>29</td>
<td>132</td>
<td>3</td>
<td>13</td>
<td>3.86</td>
</tr>
<tr>
<td>3 Honda Civic Sdn 4dr CVT LX</td>
<td>19,190</td>
<td>30</td>
<td>143</td>
<td>3</td>
<td>12.5</td>
<td>1.90</td>
</tr>
<tr>
<td>4 Hyundai Elantra 4dr Sdn Auto SE</td>
<td>18,200</td>
<td>28</td>
<td>145</td>
<td>5</td>
<td>14.8</td>
<td>3.90</td>
</tr>
</tbody>
</table>
Figure 4.19. Data Entering on Part 1 (Number of Alternatives, Criteria, and Entities of Matrix A)
4.3.4.1.2. Part 2

This part is related to entering the entities of pairwise comparison matrix of criteria which is shown by \( C \). The entities of \( C \) will be entered manually column by column. Figure 4.21 depicts how the entities of matrix \( C \) are entered and finally matrix \( C \) appears on the screen (Figure 4.22).
Figure 4.21. Part 2 of the Code Related to Data Entering (Entities of Matrix C)
The entities of matrix C may be calculated based on the weights of criteria instead of pairwise comparison of criteria. In this case, the consistency index of C is zero because all the entities of C are calculated by constant numbers instead of experts’ judgments. For example, the element \((i,j)\) of C can be calculated by \(w_i / w_j\) which is weights of criteria \(i\) divided by weights of criteria \(j\). The code in part two can be modified to enter the criteria’s weights to calculate C instead of entering the entities of the C based on the experts’ judgments (Appendix 5).

4.3.4.1.3. Part 3

The priority vector and other parameters related to the consistency evaluation of the C’s entities will also be calculated. Figure 4.23 shows part of the output created by the code.
It is evident that the value of CR is greater than 0.1; therefore, the pairwise comparison of criteria (C’s entities) should be altered to decrease CR to less than 0.1. Figure 4.24 illustrates the modified pairwise comparison matrix C and its priority vector and consistency evaluation parameters.

Figure 4.23. Priority Vector and Consistency Parameters of Matrix C

Figure 4.24. Modified Pairwise Comparison Matrix of Criteria (C)

Figure 4.25. Priority Vector and Consistency Parameters of Modified C
The entities of pairwise evaluation matrix are currently consistent because CR is less than 0.1 (Figure 4.2).

4.3.4.1.4. Part 4

The ideal value of each criterion should be defined as maximum or minimum. The maximum value of criteria can be entered H (High) or L (Low). The Matlab syntax requires that the H or L should be placed within a single quote mark. In this example, all the criteria except criteria 1 and 6 have high (maximum) ideal values (Table 4.5).

4.3.4.1.5. Part 5

This part calculates the entities of pairwise comparison matrix of alternatives for each criterion. All the entities will be included in the three dimensions parameter “a”. Section 2.4 described in detail how the pairwise comparison matrix of alternatives for each criterion can be calculated based on the data entered in parts 1, 2, and 4.

4.3.4.1.6. Part 6

The same calculations that were covered in part 3 will be repeated in this part for the pairwise comparison matrix of alternatives for each criterion. The entities of the matrices are calculated in part 5 based on the values of alternatives for each criterion. Figure 4.26 shows the results of each of the six criteria in the sample example. The consistency of pairwise comparison matrix of alternatives for each criterion is shown first. Each column
of the priority matrix includes the priority vector of each criterion. The first column of the priority matrix shows the priority vector of criterion number one, and the last column shows the priority vector of criterion number six.

Figure 4.26. Check of Consistency for Pairwise Comparison of Alternatives for each Criterion and Related Priority Vectors
4.3.4.1.7. Part 7

The final results of AHP are calculated using the quantitative values of each criterion based on the preferred criteria and their weights. The values of criteria are calculated by multiplying the priority matrix of alternatives and priority vector of criteria. Figure 4.27 indicates the result. The first value is related to the alternative one, and the last value shows the importance of the last alternative.

![Command Window](image)

Figure 4.27. Values of Alternatives

Honda is the first rank alternative while Toyota has the lowest rank. The rank of alternatives is similar to the ranks using manual calculation given in Section A4.2 of Appendix 4.

4.4. Conclusions

PROMETHEE and AHP are among the MCDM methods that are used widely in industries. These methods have various applications but, in this dissertation, PROMETHEE is used for project ranking, and AHP is used to calculate a risk factor based on the qualitative evaluation of risks.
PROMETHEE is among the commonly used MCDM methods for ranking the alternatives. It has been used in different categories including business and financial management. Portfolio formation in organizations is under this category. It is beneficial for organizations to systematically select projects that are better aligned with their goals considering all their risks.

PROMETHEE has some advantages in setting thresholds for criteria. Different preference functions alter the ranks of alternatives due to changes in pairwise comparison of alternatives considering the thresholds. Both the stepwise manual calculations and software results are compared with Ex-PROMETHEE results in the given example to be sure about the accuracy of Ex-PROMETHEE. The designed Ex-PROMETHEE can be used in conjunction with @Risk® when the probabilistic analysis of the input variables is required. The Visual PROMETHEE by itself does not have probabilistic analysis on input variables to study their influence on the rank of alternatives. Portfolio formation, which is crucial in organizations, requires probabilistic analysis to figure out the probability of achieving the organizational goals. In fact, Ex-PROMETHEE in conjunction with @Risk® helps to investigate the variation in projects’ ranks. In this way, those projects on the border line of budget restriction will be identified for further evaluation.

AHP is another MCDM method that has been used in different industries, such as the construction industry, for selecting and ranking projects. AHP is also applicable to the portfolio formation process. Selecting and ranking the projects among several candidate
projects is achievable using AHP when various qualitative and quantitative criteria are available.

AHP has some limitations in comparison to PROMETHEE. Variation of criteria in AHP is not as flexible as PROMETHEE. In fact, six different preference functions can be used for each criterion in PROMETHEE while there is no preference function for criteria in AHP. The preference functions help to include some types of restrictions on criteria, so AHP does not have this flexibility to consider restrictions on input variables.

A Matlab code for AHP is developed and explained in detail in this chapter to calculate a risk factor for each alternative based on the qualitative evaluation of risks. It is possible to develop this code for probabilistic input variables, which can be fulfilled in upcoming research.
Chapter 5: Project Portfolio Formation Case Study

5.1. Introduction

This case study describes the portfolio formation process. The objective is to demonstrate the concepts that are described in previous chapters using a realistic example. A large chemicals and plastics manufacturing organization intends to form its portfolios having a restricted budget. The strategic objectives of this organization are keeping the existing units operational based on the environmental protection agency (EPA) regulations, providing a healthy and safe environment for operators, maintaining the existing units in good working conditions and finally, increasing the productivity.

Candidate projects are categorized into three groups: Productivity, Environmental, Health, and Safety (EHS), and maintenance. Two multicriteria decision-making (MCDM) methods, PROMETHEE and analytical hierarchy process (AHP), are used to rank and select projects. These methods are used due to their appropriateness for this purpose and pervasive use in industries, including the construction industry. The preferred criteria can be categorized into four groups: finance and economic, safety, pioneer product, and risk factor. Projects’ risk factors are calculated by converting qualitative risks at different managerial levels (strategic, portfolio, program, and project) to a quantitative value using
AHP. The results of the analysis using PROMTHEE and AHP are compared to identify which one gives better consistency in results and to see which one is more applicable in portfolio formation.

This organization is studied because it has different project types. Furthermore, one of the managers of this organization kindly devoted his time to collect the required information. Despite the effort in gathering the required data, some information was not accessible due to various concerns such as competitors and trade secrets.

This organization, hereafter called ABC Corporation, was established more than 35 years ago, and it is now one of the world’s leading manufacturers of chemicals, fertilizers, and plastics. ABC Corporation has grown steadily to become one of the world’s top 100 companies. They have operations in over 40 countries around the world and are considered among the five largest diversified chemical companies in the world.

For the purpose of this case study, the required data is gathered from one of the ABC Corporation’s sites that has 17 candidate projects. There is no strategic (S) project among the 17 candidate projects. These projects are allocated in three project types: nine in productivity (P), three in EHS, and five in maintenance (M). These project types are explained in Section 3.2.2.

Different project selection methods, PROMETHEE and AHP, are examined in this case study to better understand the positive and negative points of these methodologies. The developed Matlab code is used for AHP in this case study. Furthermore, the Visual PROMETHEE software is used for PROMETHEE I and II while Ex-PROMETHEE in conjunction with @Risk is used for probabilistic analysis of input variables.
Projects in various project types should be ranked using their own set of criteria. If all projects of different project types are ranked in one bucket, some projects may be selected that are not aligned with organizational goals. This happens because a union of criteria is used to rank projects while projects do not have value for some criteria. As a result, projects in one portfolio should be autonomously ranked using their set of criteria. In this way, those projects that better meet the organizational goals will be selected to form a portfolio.

PROMETHEE is identified as a better MCDM method for project portfolio formation because of two principle reasons. First, it has flexibility in defining preference functions. These functions help to give more value to projects that are aligned with organizational goals. Second, this method gives more consistent projects’ ranks in cases of considering all projects of different types in one bucket or in separate buckets. AHP can be effectively used to calculate quantitative projects’ risk factors based on qualitative evaluation of risks at different levels of the organization.

The balanced portfolios in terms of project types and risks are formed in this case study. As mentioned before, the case study is about a site of ABC Corporation, so it is not possible to balance portfolios in terms of geographical locations and business types. ABC Corporation was not interested to share precise information on how budget is allocated among various project types. Based on information provided by ABC Corporation, EHS projects have priority over maintenance and then productivity projects. Balanced portfolios are formed using this information.
5.2. Case Study Portfolio Hierarchy

ABC Corporation’s portfolio hierarchy has three levels. The business lines are at the top level, geographical locations or sites are at the middle, and project types are at the bottom (Figure 5.1). This portfolio hierarchy is similar to what was described for an oil and gas company in Chapter 3 (Figure 3.6). Three business lines are available in this organization: plastics, fertilizers, and chemicals. These business lines form the top level portfolio categories as shown in Figure 5.1. The plastics business line has 15 sites in different geographical locations, the fertilizers business line has eight sites and chemicals have 17 sites around the world. Each of these sites has four different project types, which are productivity (P), Environmental, Health, and Safety (EHS), maintenance (M), and strategic (S). These project types form the low level portfolios. This case study is about one of the ABC Corporation’s plastic sites.

![Figure 5.1. Sample Portfolio Categories in this Case Study](image-url)
5.3.  Methodology

This case study is arranged to form portfolios in three different cases to understand which one is applicable for portfolio formation. The cases are the followings:

**Case I:** All project types are ranked considering a set of preferred criteria for all projects.

**Case II:** Projects are ranked based on their types and their related preferred criteria while the budget is allocated according to project types.

**Case III:** Projects are ranked based on their types with their related preferred criteria while the budget is allocated according to portfolio categories.

5.3.1.  Case I: Prioritizing Projects with One Set of Criteria

In this case, three different types of projects (productivity, EHS, and maintenance) are considered together to be ranked and selected using a set of preferred criteria. This set of criteria is a union of criteria related to different project types, which are bottom level portfolios. In this way, some projects do not have values for all the criteria because different project types have various preferred criteria. Considering all the projects together, the union of preferred criteria for different project types will be considered in the prioritization process.

It is shown that ranking all the project types with the union of preferred criteria eliminates some important projects such as EHS projects. In fact, EHS projects are paramount for keeping existing facilities safe in all aspects, but they are ranked at the bottom of the project list. It means that all the EHS projects will not be selected to form the portfolios.

It will be shown that ranking all projects in different project types together with a set of
preferred criteria ignores selecting some important projects from the list of candidate projects.

Case II is defined to form the portfolios based on different project types. The candidate projects are ranked within each portfolio with their related criteria. Considering the budget ceilings, the top ranked projects are selected to form a portfolio. For example, five maintenance projects are considered in one portfolio to be ranked using three preferred criteria: net present value (NPV), safety risk, and criticality score.

Seven quantitative and qualitative criteria are suggested by ABC Corporation to rank candidate projects. Most of these criteria are explained in Section 3.2.5.1. These preferred criteria to evaluate the alternatives (17 projects) are:

5. ROI  6. Criticality Score  7. Amount of Damages (consequential damages)

As can be observed, two of these criteria are qualitative in nature: pioneer product and safety risk. The remaining criteria are all quantitative. Most of the criteria such as internal rate of return (IRR), NPV, safety risk, ROI, criticality score, and amount of damages criterion are suggested by ABC Corporation. Some of these criteria such as IRR, NPV, and ROI are also identified in the Construction Industry Institute research report (CII RR303-3, expected 2015) through survey and interviews. Pioneer product criterion is suggested in this dissertation because organizations with new products always have competitive advantages. A criterion similar to pioneer product has been used in a research called “Level of Technology Novelty” (Nowak, 2005) as shown in Table 3.2. Therefore, including
pioneer product criterion in the project ranking process increases the chance of selecting pioneer projects to form a portfolio.

IRR, NPV, and/or ROI are usually used in organizations to rank projects. Safety is recognized as a significant area in all organizations, while pioneer product is important in manufacturing and production organizations. Criticality score is related to the probability of failure for equipment, a part of the operation units, or whole units. The amount of damages is also important because ignoring some minor projects necessary for the functioning of operating units may cause serious disasters that can cost considerable amounts of money for an organization.

Considering all the project types together, seven criteria are used to rank the projects. Four criteria, namely IRR, NPV, ROI, and pioneer product are related to productivity projects. The maintenance projects have three criteria: NPV, safety risk, and criticality score. Two criteria are for EHS projects: safety risk and amount of damages. Table 5.1 illustrates which criteria are applicable for each project type. Two criteria, NPV and safety risk, are common between maintenance and EHS projects. Other criteria are applicable to just one project type.

<table>
<thead>
<tr>
<th>Project Type</th>
<th>IRR</th>
<th>NPV</th>
<th>Pioneer Product</th>
<th>Safety Risk</th>
<th>ROI-10 yrs</th>
<th>Criticality Score</th>
<th>Expected Damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>EHS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>✓</td>
</tr>
</tbody>
</table>
The qualitative criteria, pioneer product and safety risk, are evaluated using different Likert scales. The safety risk criterion is evaluated with three scales such as high (H), medium (M), or low (L). It demonstrates project’s influence on the safe operation of a facility. In other words, if safety risk of a facility is high, the project is of high importance.

A pioneer product is evaluated qualitatively with yes (Y) or no (N) answers. A Likert scale can also be used based on the probability of success of a pioneer product at the time that it goes to market. It means that those pioneer products with high probability of success will be evaluated using high scores on the Likert scale.

The criticality score is based on the probability of an equipment failure. Table 5.2 shows the criticality score for different failure probabilities on a 10-point Likert scale. The value of the criticality score for each probability category is for the maximum probability. Several studies have been done to quantitatively evaluate the equipment’s criticality score based on their operational conditions. These studies used a variety of possible risks to identify a proper maintenance schedule (Hu et al., 2009; Tixier et al., 2002).

<table>
<thead>
<tr>
<th>Probability (P)</th>
<th>0% ≤ P &lt; 20%</th>
<th>20% ≤ P &lt; 40%</th>
<th>40% ≤ P &lt; 60%</th>
<th>60% ≤ P &lt; 80%</th>
<th>80% ≤ P ≤ 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criticality Score</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>
Basic required information for each project to use a MCDM method is depicted in Table 5.3. Values of quantitative or qualitative criteria for different projects are listed alongside them.

Table 5.3. Values of Criteria for Different Alternatives

<table>
<thead>
<tr>
<th>Project Type</th>
<th>Criteria</th>
<th>1 IRR (%)</th>
<th>2 NPV ($ million)</th>
<th>3 Pioneer Product</th>
<th>4 Safety Risk</th>
<th>5 ROI-10 yrs</th>
<th>6 Criticality Score</th>
<th>7 Expected Damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>P_1</td>
<td>0.0</td>
<td>2177.0</td>
<td>N</td>
<td>M</td>
<td>0.0</td>
<td>6.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_2</td>
<td>37.5</td>
<td>37526.0</td>
<td>Y</td>
<td>L</td>
<td>6.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_3</td>
<td>71.6</td>
<td>6000.0</td>
<td>N</td>
<td>L</td>
<td>9.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>M</td>
<td>P_4</td>
<td>0.0</td>
<td>618.0</td>
<td>N</td>
<td>L</td>
<td>0.0</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_5</td>
<td>25.3</td>
<td>1095.0</td>
<td>N</td>
<td>L</td>
<td>1.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_6</td>
<td>76.9</td>
<td>840.0</td>
<td>Y</td>
<td>L</td>
<td>3.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>M</td>
<td>P_7</td>
<td>0.0</td>
<td>59938.0</td>
<td>N</td>
<td>L</td>
<td>0.0</td>
<td>7.0</td>
<td>0.0</td>
</tr>
<tr>
<td>EHS</td>
<td>P_8</td>
<td>0.0</td>
<td>0.0</td>
<td>N</td>
<td>H</td>
<td>0.0</td>
<td>0.0</td>
<td>1</td>
</tr>
<tr>
<td>M</td>
<td>P_9</td>
<td>0.0</td>
<td>510.0</td>
<td>N</td>
<td>L</td>
<td>0.0</td>
<td>9.0</td>
<td>0.0</td>
</tr>
<tr>
<td>M</td>
<td>P_10</td>
<td>0.0</td>
<td>5432.0</td>
<td>N</td>
<td>M</td>
<td>0.0</td>
<td>3.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_11</td>
<td>425.0</td>
<td>10293.0</td>
<td>Y</td>
<td>L</td>
<td>55</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>EHS</td>
<td>P_12</td>
<td>0.0</td>
<td>0.0</td>
<td>N</td>
<td>H</td>
<td>0.0</td>
<td>0.0</td>
<td>2.45</td>
</tr>
<tr>
<td>EHS</td>
<td>P_13</td>
<td>0.0</td>
<td>0.0</td>
<td>N</td>
<td>M</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>P</td>
<td>P_14</td>
<td>70.6</td>
<td>1950.0</td>
<td>N</td>
<td>L</td>
<td>11.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_15</td>
<td>41.7</td>
<td>72503.0</td>
<td>Y</td>
<td>L</td>
<td>6.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_16</td>
<td>50.0</td>
<td>2000.0</td>
<td>N</td>
<td>L</td>
<td>1.8</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>P</td>
<td>P_17</td>
<td>929.0</td>
<td>2012.59</td>
<td>N</td>
<td>L</td>
<td>6.4</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
ROI over a 10-year period is calculated using the provided information on the total installation cost (TIC) of a project and its payback period. The information in the pioneer product, criticality score, and expected damages columns is based on the manager’s opinion.

In Table 5.3, the ideal row under the criteria row shows that the minimum or maximum value of a criterion adds more value to an alternative to bring the alternative to a higher rank. For example, the ideal value of IRR is maximum, this means that the higher the IRR value, the higher the rank of an alternative. The pioneer product is a qualitative criterion, and its ideal value is “Yes,” which means projects with pioneer products have higher priority.

The candidate projects listed in Table 5.3 are considered together in one bucket as shown in Figure 5.2. Each of the small symbolic Gantt charts shows one of the candidate projects in this figure. Three different types of projects are considered for selecting and forming the portfolios in this site.

Figure 5.2. All Projects in One Bucket
5.3.1.1. Project Selection in Case I Using PROMETHEE

PROMETHEE methodology is explained in detail in Chapter 4. In this section, the application of this methodology is explained to better understand how a MCDM method can be used to rank the candidate projects.

All the required information related to the preferences section in the PROMETHEE interface should be defined to rank the projects and analyze alternatives. Besides the ideal value of each criterion, which is defined in Table 5.4, weights of criteria, preference functions, and thresholds are shown in Figure 5.3. The most important criterion is considered to be “Safety” with the highest weight of five. The lowest weight is two given to “IRR” and “ROI”. Due to the organization’s confidentiality code, the preference functions and their thresholds for each criterion are assumed according to Table 5.4. The reasons behind assuming the preference functions are also explained in this table.

![Figure 5.3. The Preferences for each Criterion](image-url)
Table 5.4. Preference Functions Defined for Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Preference Function</th>
<th>Threshold</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRR Level</td>
<td>Min: 20; Max: 50</td>
<td>-</td>
<td>Assumed that pairwise difference below 20 is not acceptable in plastic business and above 50 is strict</td>
</tr>
<tr>
<td>NPV V-Shape</td>
<td>Max: 2000</td>
<td>-</td>
<td>Assumed a linear pairwise difference variation but above 2000 is excellent. The higher the NPV, the better the alternative</td>
</tr>
<tr>
<td>ROI-10 yrs V-Shape</td>
<td>Max: 2</td>
<td>-</td>
<td>The higher the ROI, the better the alternative</td>
</tr>
<tr>
<td>Pioneer Product</td>
<td>Usual</td>
<td>-</td>
<td>It is qualitative with two scales: Yes and No</td>
</tr>
<tr>
<td>Criticality Score</td>
<td>V-Shape</td>
<td>Max: 10</td>
<td>It is intended to give higher values to those alternatives with higher criticality score</td>
</tr>
<tr>
<td>Safety Risk Level</td>
<td>Level</td>
<td>Min: 1; Max: 2</td>
<td>It is qualitative with three scales (low, medium, high) that the level can best describe the pairwise differences</td>
</tr>
<tr>
<td>Amount of Damage</td>
<td>V-Shape</td>
<td>Max: 3</td>
<td>A linear trend is considered for alternatives. The higher the amount of damage, the higher the priority of alternative.</td>
</tr>
</tbody>
</table>

The information shown in Table 5.3 is used in software for different alternatives and criteria. Figure 5.4 exhibits the values of seven criteria for 17 alternatives.

The alternatives (projects) are shown with three symbols in Figure 5.4. The blue square shows maintenance projects. The yellow circle shows productivity projects and the purple diamond shows EHS projects.
The projects’ ranks based on the net flow values are shown in Figure 5.5. Projects are ranked based on parameters such as criteria’s values, criteria’s weights, and preference.
functions. These parameters influence the projects’ net flow values, which are ranked accordingly.

The EHS projects (P8, P12, and P13) shown with purple diamonds in Figure 5.5 are not among the top priority projects. Even though two of the EHS projects, P12 and P8, have high safety impact (which means that these are crucial for operating plants), they are ranked 9 and 11 respectively. The other EHS project, P13, with medium safety impact is at the bottom of the ranked projects. EHS projects are ranked low because they have values for just two criteria: safety and amount of damages, while their other criteria are zero.

![Figure 5.5. Projects’ Ranks with Seven Criteria](image)

Changing the preferred criteria will affect projects’ ranks. For example, if the ROI is eliminated from the preferred criteria list, the ranks of the projects change (Figure 5.6).
This change illustrates the importance of considering a set of appropriate preferred criteria in project ranking.

![Figure 5.6. Projects’ Ranks with Six Criteria (ROI Eliminated)](image)

Even though ROI and IRR are closely related, using both criteria to evaluate candidate projects has influence on the results and helps to refine projects’ ranks. Figure 5.7 shows the effect of eliminating criteria on projects’ ranks using PROMETHEE. Criticality score and the amount of damages have the lowest weight among the seven preferred criteria. These criteria are ignored one after another, and then criteria with higher weights are eliminated to study projects’ ranks. Safety, which has the highest rank, is the last criterion considered to rank the candidate projects. It is apparent that ignoring even the low weight
criteria, which are amount of damages and criticality score in this case study, has an influence on projects’ ranks.

![Preferred Criteria](image)

**Figure 5.7. The Rank of Candidate Projects with Various Numbers of Preferred Criteria**

Criteria’s weights should be decided based on the weights of criteria’s areas when criteria are correlated. In this way, several related criteria may be considered with rational weights. For example, seven criteria can be allocated to three areas in this case study: 1) Finance/economic, 2) safety, and 3) miscellaneous. Giving a weight of 39% to each of the finance/economic and safety areas, the remaining 22% will be given to miscellaneous.
These weights should be divided among criteria in each area. Table 5.5 indicates criteria’s weights based on areas’ weight.

<table>
<thead>
<tr>
<th>No.</th>
<th>Criteria</th>
<th>Areas</th>
<th>Areas’ Weight (%)</th>
<th>Criteria’s Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IRR</td>
<td>Finance/Economic</td>
<td>39</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>NPV</td>
<td>Finance/Economic</td>
<td>39</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>ROI</td>
<td></td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>Pioneer</td>
<td>Miscellaneous</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Safety</td>
<td>Safety</td>
<td>39</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>Criticality Score</td>
<td></td>
<td>39</td>
<td>5.5</td>
</tr>
<tr>
<td>7</td>
<td>Amount of damages</td>
<td></td>
<td></td>
<td>5.5</td>
</tr>
</tbody>
</table>

The criteria’s weights can be converted to integer weights by maintaining the same ratios between them. In this case study, the integer weights that can be used in PROMETHEE are listed in Table 5.6. The integer weights are calculated by multiplying criteria’s weights to a hypothetical sum of the criteria’s weights. For example, IRR integer weight is $11\% \times 18 = 2$, if the sum of integer weights is considered 18. The integer weights are those considered in PROMETHEE as shown in Figure 5.4.
Table 5.6. Integer Criteria’s Weights Using % of Criteria’s Weights

<table>
<thead>
<tr>
<th>No.</th>
<th>Criteria</th>
<th>Criteria’s Weights (%)</th>
<th>Integer Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IRR</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>NPV</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>ROI</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Pioneer</td>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Safety</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Criticality Score</td>
<td>5.5</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Amount of damages</td>
<td>5.5</td>
<td>1</td>
</tr>
</tbody>
</table>

5.3.1.1.1.  **PROMETHEE V**

The net flow values calculated in PROMETHEE I and II are used in PROMETHEE V to optimize the selection of projects under budget constraints. PROMETHEE V is used to select the most valuable projects considering the budget constraints. The objective function in PROMETHEE V is to maximize the sum of the net flow scores for the selected projects. It is designed based on a 0-1 linear programming, in which the objective function is to maximize the sum of the net flows of selected projects (Brans and Mareschal, 1994; Mareschal and Brans, 1992). The 0-1 linear programming is a specific case of integer programming where some or all of the variables are binary.

Considering a maximum portfolio budget of $1,000 million, the optimized portfolio of projects can be identified. The estimated budget of the projects is listed in Table 5.7. Using these figures for the project budgets, the selected projects are highlighted in green in Figure 5.8.
Table 5.7. The Estimated Budget of Projects (million $)

<table>
<thead>
<tr>
<th>P_1</th>
<th>P_2</th>
<th>P_3</th>
<th>P_4</th>
<th>P_5</th>
<th>P_6</th>
<th>P_7</th>
<th>P_8</th>
<th>P_9</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>56</td>
<td>300</td>
<td>85</td>
<td>547</td>
<td>175</td>
<td>50.7</td>
<td>165.5</td>
<td>63.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P_{10}</th>
<th>P_{11}</th>
<th>P_{12}</th>
<th>P_{13}</th>
<th>P_{14}</th>
<th>P_{15}</th>
<th>P_{16}</th>
<th>P_{17}</th>
</tr>
</thead>
<tbody>
<tr>
<td>511.1</td>
<td>20</td>
<td>42</td>
<td>424</td>
<td>42.5</td>
<td>52</td>
<td>53.8</td>
<td>66</td>
</tr>
</tbody>
</table>

Figure 5.8. Selected Projects by the Software with Positive Net Flow

On the right side of Figure 5.8 under “Optimal,” the total cost of selected projects is $711.5 million, which is less than the budget ceiling ($1 billion). PROMETHEE V algorithm selects those projects with positive net flow value so the selected projects’ budgets are less than the budget ceiling. Using a trial-and-error process, some other projects may be added to the project portfolio. In the process of trial-and-error, projects with higher net
flow should be selected first because they better align with the preferred criteria to achieve the budget ceiling. If selecting one project pushes the required budget over the budget ceiling, other available projects with the highest net flow values should be selected. When the required budget is again over the budget ceiling, then the next project with a high net flow should be selected to keep the required budget under the budget ceiling. This process should be iterated to select projects with higher net flow values while monitoring that the required budget is under the ceiling.

In Figure 5.9, the “Optimal” column displays the optimal solution, and the “Compare” column can be used to change the selection for comparison and make what-if analyses. The "Total" row indicates the value of the objective function. The right table illustrates the left and right hand sides (LHS and RHS) of the constraints for both the optimal and the compared selections. All the constraint violations appear in red.

The “Compare” column on the right side of Figure 5.9 indicates the results of the trial-and-error process. This column shows that the number of selected projects within the budget ceiling can increase to 11 instead of seven. These seven projects are selected by the software based on the positive net flow values of candidate projects and the budget constraint. The P1, P7, P12, and P16 are selected by trial-and-error, and the total required budget is now $978.0 million instead of $711.5 million, which is close to the budget ceiling. No more projects can be added to the portfolio because the remaining budget for projects is equal to $22.0 million ($1000 - $978.0 = $22.0), which is less than the required budget of each of the remaining projects.
Figure 5.9. Selected Projects to Reach the Budget Ceiling

The green projects in Figure 5.9 in the “Compare” column will be included in the portfolio. Figure 5.10 shows the selected projects out of the bucket of candidate projects to form the project portfolio considering the budget ceiling. The projects’ ranks are shown in Figure 5.5.
5.3.1.2. Project Selection Using AHP in Case I

AHP is another MCDM method that can be used for project selection and portfolio formation. This method has a simpler mathematical concept explained in Chapter 4. This section uses AHP to prioritize the projects in one bucket considering a set of preferred criteria explained in Section 5.3.1.

In AHP, the comparison matrix will be built using quantitative values of criteria. Many criteria have zero values as shown in Table 5.3, which will result in some entities with infinity values. To avoid this issue, when maximum value is ideal for a criterion, the zeroes will be substituted with small numbers, because smaller numbers have less influence on projects’ ranks. Otherwise, if a criterion with minimum value is ideal, the zeroes should be substituted with large numbers to prevent infinity values in the pairwise comparison matrix and minimize the influence of that criterion on projects’ ranks. Considering this point, Figure 5.11 shows the values of criteria for different alternatives in matrix “A”.

Matrix “A” is calculated using Matlab, in which the code is given in Appendix 5. Each row includes the criteria values for a project.
The pairwise comparison matrix of criteria is shown in Figure 5.12. This matrix is calculated based on the weights of criteria defined in Section 5.3.1. The consistency index (CI) and consistency ratio (CR) are zero because the pairwise comparison matrix of criteria is calculated based on criteria’s weights and their reciprocals. However, if pairwise comparison matrix is formed based on experts’ opinions, CI and CR should be checked to be sure about the consistency of evaluations. The detail of calculations is available in Section A4.2 of Appendix 4.
The priority values of 17 candidate projects using AHP method is shown on the left side of Table 5.8. Project ranks are shown on the right side of this table.

### Table 5.8. Projects’ Ranks Using AHP

<table>
<thead>
<tr>
<th>Rank</th>
<th>Value of Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P₁₁ 0.15713</td>
</tr>
<tr>
<td>2</td>
<td>P₁₅ 0.13598</td>
</tr>
<tr>
<td>3</td>
<td>P₂  0.10670</td>
</tr>
<tr>
<td>4</td>
<td>P₇  0.07522</td>
</tr>
<tr>
<td>5</td>
<td>P₆  0.07513</td>
</tr>
<tr>
<td>6</td>
<td>P₁₂ 0.07305</td>
</tr>
<tr>
<td>7</td>
<td>P₁₇ 0.06813</td>
</tr>
<tr>
<td>8</td>
<td>P₁₀ 0.05573</td>
</tr>
<tr>
<td>9</td>
<td>P₈  0.05037</td>
</tr>
<tr>
<td>10</td>
<td>P₁  0.03729</td>
</tr>
<tr>
<td>11</td>
<td>P₃  0.03094</td>
</tr>
<tr>
<td>12</td>
<td>P₉  0.03052</td>
</tr>
<tr>
<td>13</td>
<td>P₁₄ 0.02973</td>
</tr>
<tr>
<td>14</td>
<td>P₁₃ 0.02472</td>
</tr>
<tr>
<td>15</td>
<td>P₁₆ 0.01776</td>
</tr>
<tr>
<td>16</td>
<td>P₄  0.01620</td>
</tr>
<tr>
<td>17</td>
<td>P₅  0.01541</td>
</tr>
</tbody>
</table>

![Pairwise Comparison Matrix of Criteria](image-url)
5.3.1.3. Comparing Project Selection Using PROMETHEE and AHP

The two MCDM methods do not give similar results. PROMETHEE methodology ranks the candidate projects, and 10 projects will be selected considering the budget ceiling. AHP ranks the candidate projects, and eight projects are selected.

Table 5.9. The Rank of Selected Projects Using PROMETHEE and AHP

<table>
<thead>
<tr>
<th>Rank</th>
<th>PROMETHEE</th>
<th>AHP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project</td>
<td>Cost</td>
</tr>
<tr>
<td>1</td>
<td>P_{11}</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>P_{15}</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>P_{2}</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>P_{6}</td>
<td>175</td>
</tr>
<tr>
<td>5</td>
<td>P_{3}</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>P_{17}</td>
<td>66</td>
</tr>
<tr>
<td>7</td>
<td>P_{14}</td>
<td>42.5</td>
</tr>
<tr>
<td>8</td>
<td>P_{7}</td>
<td>50.7</td>
</tr>
<tr>
<td>9</td>
<td>P_{12}</td>
<td>42</td>
</tr>
<tr>
<td>10</td>
<td>P_{16}</td>
<td>53.8</td>
</tr>
<tr>
<td>11</td>
<td>P_{8}</td>
<td>165.5</td>
</tr>
<tr>
<td>12</td>
<td>P_{10}</td>
<td>511.1</td>
</tr>
<tr>
<td>13</td>
<td>P_{1}</td>
<td>120</td>
</tr>
<tr>
<td>14</td>
<td>P_{5}</td>
<td>547</td>
</tr>
<tr>
<td>15</td>
<td>P_{9}</td>
<td>63.4</td>
</tr>
<tr>
<td>16</td>
<td>P_{4}</td>
<td>85</td>
</tr>
<tr>
<td>17</td>
<td>P_{13}</td>
<td>424</td>
</tr>
</tbody>
</table>

PROMETHEE suggests P_1, P_3, P_8, and P_{14} instead of P_{10} selected by AHP. The top three projects have identical ranks in both methods; P_4 and P_5 are inverted while priorities are completely different from rank six on. A comparison of project ranks using the two MCDM
methods is shown in Table 5.9; moreover, the selected projects from the list of candidate projects are depicted with gray shading.

The total required budgets of selected projects for PROMETHEE and AHP are $978.0 million and $972.8 million, respectively. PROMETHEE selects four smaller projects (P₁, P₃, P₁₄, and P₁₆) instead of one large project (P₁₀) selected by AHP.

This example shows that applying different MCDM methods can produce various outcomes. Those projects that have significant advantages appear at the top of the list for both of these methods. Other alternatives have completely different ranks. PROMETHEE is a more flexible methodology because six different types of preference functions can be used for each criterion.

Figure 5.7 illustrated the influence of the number of criteria on projects’ ranks using PROMETHEE. Table 5.10 indicates selected projects in seven different cases as shown in Figure 5.7 considering the budget ceiling. The number of criteria changes in each case. The first column indicates selected projects when all criteria are used to rank projects, then other criteria are ignored from the list of preferred criteria one by one considering their weights.

Selected projects are identical in the second and third columns when criticality score is among preferred criteria or omitted from the list of criteria. The least number of candidate projects is selected when all the criteria except safety risk (safety) are ignored to rank the projects. The total required budget for each case is less than the budget ceiling ($1000 million).
Table 5.10. Selected Projects for Various Numbers of Preferred Criteria

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>978 982 982 970 981 981 980</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Budget</th>
</tr>
</thead>
</table>

5.3.2. Case II: Prioritizing Projects based on Project Type with Balanced Budget on Project Types

In the previous case, all the projects are considered in one bucket, and they are evaluated based on a set of preferred criteria. This shows that some important EHS projects are at the bottom of prioritized projects and will not be selected due to the budget ceiling. The main reason is that EHS projects have fewer criteria, safety risk and amount of damages, compared to three criteria for maintenance and four criteria for productivity projects.
Table 5.9 shows that the final list of projects to form a portfolio does not include two of the EHS projects (P8, P12). One way to resolve problems of this type is to evaluate projects with the same preferred criteria together in one bucket. Based on the data in Table 5.3, EHS projects do not have any criteria except for “safety risks” and “amount of damages.” It is logical to separate them from the list of 17 projects and rank them in one bucket, because all EHS projects have values for these two criteria. Besides EHS projects, the productivity and maintenance projects could be separated and evaluated using their own preferred criteria.

5.3.2.1. Promoting Portfolio Formation

The 17 projects can be grouped into three buckets based on their project types. One bucket is for productivity projects that have value for all the five criteria (IRR, NPV, Safety Risk, Pioneer Product, ROI), another is for EHS projects with two preferred criteria (Safety and Amount of Damages), and the last bucket is for maintenance projects with three preferred criteria (NPV, Safety Risk, and Criticality Score). Figure 5.13 indicates three buckets of project types.

![Figure 5.13. The Candidate Projects in Three Buckets for Different Project Types](image-url)
Tables 5.11, 5.12, and 5.13 below show the lists of projects and their quantitative and qualitative criteria for productivity, EHS, and maintenance projects.

Table 5.11. The List of Projects in Productivity Bucket

<table>
<thead>
<tr>
<th>Criteria</th>
<th>IRR (%)</th>
<th>NPV ($ million)</th>
<th>Pioneer Product</th>
<th>ROI-10 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Projects</td>
<td>Max.</td>
<td>Max.</td>
<td>Yes</td>
<td>Max.</td>
</tr>
<tr>
<td>P2</td>
<td>37.5</td>
<td>37526.00</td>
<td>Y</td>
<td>6.3</td>
</tr>
<tr>
<td>P3</td>
<td>71.6</td>
<td>6000.00</td>
<td>N</td>
<td>9.9</td>
</tr>
<tr>
<td>P5</td>
<td>25.3</td>
<td>1095.00</td>
<td>N</td>
<td>1.5</td>
</tr>
<tr>
<td>P6</td>
<td>76.9</td>
<td>840.00</td>
<td>N</td>
<td>3.1</td>
</tr>
<tr>
<td>P11</td>
<td>425.0</td>
<td>10293.00</td>
<td>Y</td>
<td>55.0</td>
</tr>
<tr>
<td>P14</td>
<td>70.6</td>
<td>1950.00</td>
<td>N</td>
<td>11.9</td>
</tr>
<tr>
<td>P15</td>
<td>41.7</td>
<td>72503.00</td>
<td>Y</td>
<td>6.6</td>
</tr>
<tr>
<td>P16</td>
<td>50.0</td>
<td>2000.00</td>
<td>N</td>
<td>1.8</td>
</tr>
<tr>
<td>P17</td>
<td>929.0</td>
<td>2012.59</td>
<td>N</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 5.12. The List of Projects in EHS Bucket

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Safety Risk</th>
<th>Amount of Damages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Projects</td>
<td>High</td>
<td>Max.</td>
</tr>
<tr>
<td>P8</td>
<td>H</td>
<td>1.00</td>
</tr>
<tr>
<td>P12</td>
<td>H</td>
<td>2.45</td>
</tr>
<tr>
<td>P13</td>
<td>M</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Table 5.13. The List of Projects in Maintenance Bucket

<table>
<thead>
<tr>
<th>Criteria</th>
<th>NPV ($ million)</th>
<th>Safety Risk</th>
<th>Criticality Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Projects</td>
<td>Max.</td>
<td>High</td>
<td>Max.</td>
</tr>
<tr>
<td>P₁</td>
<td>2177.00</td>
<td>M</td>
<td>6.0</td>
</tr>
<tr>
<td>P₄</td>
<td>618.00</td>
<td>L</td>
<td>2.0</td>
</tr>
<tr>
<td>P₇</td>
<td>59938.00</td>
<td>L</td>
<td>7.0</td>
</tr>
<tr>
<td>P₉</td>
<td>510.00</td>
<td>L</td>
<td>9.0</td>
</tr>
<tr>
<td>P₁₀</td>
<td>5432.00</td>
<td>M</td>
<td>3.0</td>
</tr>
</tbody>
</table>

For ABC Corporation, EHS projects have top priority in this specific site. Required budget is allocated to the EHS bucket to execute all these projects. The remaining budget will be divided between other buckets. It is assumed that the maintenance bucket gets 60% of the remaining budget while productivity bucket receives 40% of the remaining budget. This assumption totally varies from organization to organization based on their strategy. Table 5.14 shows the amount of budget allocated to each project type. The total budget is $1000 million.

Table 5.14. The Budget Ceiling for Different Project Types ($ million)

<table>
<thead>
<tr>
<th>Project Type</th>
<th>Productivity</th>
<th>EHS</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budget</td>
<td>147.4</td>
<td>631.5</td>
<td>221.1</td>
</tr>
</tbody>
</table>
5.3.2.2. Project Selection in Case II Using PROMETHEE

The weights and preference functions are the same as Case I for different criteria to calculate the priority of projects. Considering the new project buckets, the ranks of productivity, EHS, and maintenance projects using PROMETHEE method are shown in Figures 5.14, 5.15, and 5.16.

Figure 5.14. Projects’ Ranks in Productivity Bucket

Figure 5.15. Projects’ Ranks in EHS Bucket
Using PROMETHEE V, selected projects from each bucket can be identified considering the budget ceilings in Table 5.14. Figures 5.17, 5.18, and 5.19 illustrate selected projects from the list of candidate projects in each of the productivity, EHS, and maintenance buckets.
The “Compare” column indicates the selected projects for each portfolio. Three projects from the productivity bucket (P2, P11, P15), all the EHS projects (P8, P12, P13), and two projects from the maintenance bucket (P1, P7) are being selected to form the portfolios. Figure 5.20 depicts the formation of three portfolios.
Comparing the methods used in Cases I and II, it can be anticipated that the results will be completely different. In Case I, 10 projects P2, P3, P6, P7, P8, P11, P12, P14, P15, and P17 are selected considering one set of preferred criteria and comparing all projects together simultaneously. One project is maintenance, two projects are EHS, and the remaining projects are productivity. In Case II, eight projects are selected: three of the
productivity projects (P2, P11, and P15), three of the EHS projects (P8, P12, and P13), and two of the maintenance projects (P1 and P7). In Case II, the restricted budget is allocated according to the weight of each project type.

Table 5.15 compares the selected projects in Cases I and II. In Case II, all the important projects according to the organizational goals are selected. The assumed strategy for this case study is to execute all the EHS projects, and then 60% of the remaining budget is allocated to maintenance projects and 40% to productivity projects. Comparing column “One” and “Two” in Table 5.15 indicates that there is a balance in terms of project types. Those projects that are better aligned with organizational strategy are selected to form the portfolios.

Table 5.15. Comparison of Selected Projects in Cases I and II Using PROMETHEE

<table>
<thead>
<tr>
<th>Project Type</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>P_{11}, P_{15}, P_{2}, P_{3}, P_{6}, P_{14}, P_{17}</td>
<td>P_{11}, P_{15}, P_{2}</td>
</tr>
<tr>
<td>Maintenance</td>
<td>P_{1}</td>
<td>P_{1}, P_{7}</td>
</tr>
<tr>
<td>EHS</td>
<td>P_{8}, P_{12}</td>
<td>P_{8}, P_{12}, P_{13}</td>
</tr>
</tbody>
</table>

5.3.2.3. Project Selection in Case II Using AHP

AHP is explained in detail in Chapter 4. A Matlab code is developed to be used for this method. This section is prepared based on the results of the Matlab code, which is available in Appendix 5.

Three matrices for different project types should be defined to use AHP method and calculate the priority of projects within each project type. The matrices are based on the
information in Tables 5.11, 5.12, and 5.13. Figures 5.21, 5.22, and 5.23 show the values of criteria for different project types, productivity, EHS, and maintenance. These figures present the output of the Matlab software.

<table>
<thead>
<tr>
<th>IRR</th>
<th>NPV</th>
<th>Pioneer</th>
<th>ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5</td>
<td>37526</td>
<td>1</td>
<td>6.3</td>
</tr>
<tr>
<td>71.6</td>
<td>6000</td>
<td>0.0001</td>
<td>9.9</td>
</tr>
<tr>
<td>25.3</td>
<td>1095</td>
<td>0.0001</td>
<td>1.5</td>
</tr>
<tr>
<td>76.9</td>
<td>840</td>
<td>0.0001</td>
<td>3.1</td>
</tr>
<tr>
<td>425</td>
<td>10293</td>
<td>1</td>
<td>55</td>
</tr>
<tr>
<td>70.6</td>
<td>1950</td>
<td>0.0001</td>
<td>11.9</td>
</tr>
<tr>
<td>41.7</td>
<td>72503</td>
<td>1</td>
<td>6.6</td>
</tr>
<tr>
<td>50</td>
<td>2000</td>
<td>0.0001</td>
<td>1.8</td>
</tr>
<tr>
<td>929</td>
<td>2012.6</td>
<td>0.0001</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Figure 5.21. The Values of Criteria for Different Productivity Projects

<table>
<thead>
<tr>
<th>IRR</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2.45</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 5.22. The Values of Criteria for Different EHS Projects
The pairwise comparison matrices of criteria for different project types are shown in Figures 5.24, 5.25, and 5.26. These matrices are calculated using the criteria’s weights defined in Section 5.3.1. The Criticality Index and the Criticality Ratio of these matrices are both zero because the matrices are created based on the criteria’s weights and their reciprocals.
The projects’ values in each bucket are given in Tables 5.16, 5.17, and 5.18. These tables are for productivity, EHS, and maintenance projects respectively. The projects’ ranks are also shown alongside the projects’ AHP values.
Table 5.16. The Rank of Productivity Projects Using AHP

<table>
<thead>
<tr>
<th>Value of Projects</th>
<th>Rank</th>
<th>Value of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_2 0.21256</td>
<td></td>
<td>P_15 1 0.28461</td>
</tr>
<tr>
<td>P_3 0.03730</td>
<td></td>
<td>P_11 2 0.28439</td>
</tr>
<tr>
<td>P_5 0.00756</td>
<td></td>
<td>P_2 3 0.21256</td>
</tr>
<tr>
<td>P_6 0.01531</td>
<td></td>
<td>P_17 4 0.11323</td>
</tr>
<tr>
<td>P_{11} 0.28439</td>
<td></td>
<td>P_3 5 0.03730</td>
</tr>
<tr>
<td>P_{14} 0.03251</td>
<td></td>
<td>P_{14} 6 0.03251</td>
</tr>
<tr>
<td>P_{15} 0.28461</td>
<td></td>
<td>P_6 7 0.01531</td>
</tr>
<tr>
<td>P_{16} 0.01253</td>
<td></td>
<td>P_{16} 8 0.01253</td>
</tr>
<tr>
<td>P_{17} 0.11323</td>
<td></td>
<td>P_5 9 0.00756</td>
</tr>
</tbody>
</table>

Table 5.17. The Rank of EHS Projects Using AHP

<table>
<thead>
<tr>
<th>Value of Projects</th>
<th>Rank</th>
<th>Value of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{8} 0.35945</td>
<td></td>
<td>P_{12} 1 0.42752</td>
</tr>
<tr>
<td>P_{12} 0.42752</td>
<td></td>
<td>P_{8} 2 0.35945</td>
</tr>
<tr>
<td>P_{13} 0.21303</td>
<td></td>
<td>P_{13} 3 0.21303</td>
</tr>
</tbody>
</table>

Table 5.18. The Rank of Maintenance Projects Using AHP

<table>
<thead>
<tr>
<th>Value of Projects</th>
<th>Rank</th>
<th>Value of Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{1} 0.19399</td>
<td></td>
<td>P_{7} 1 0.39910</td>
</tr>
<tr>
<td>P_{4} 0.09060</td>
<td></td>
<td>P_{10} 2 0.19744</td>
</tr>
<tr>
<td>P_{7} 0.39910</td>
<td></td>
<td>P_{1} 3 0.19399</td>
</tr>
<tr>
<td>P_{9} 0.11888</td>
<td></td>
<td>P_{9} 4 0.11888</td>
</tr>
<tr>
<td>P_{10} 0.19744</td>
<td></td>
<td>P_{4} 5 0.09060</td>
</tr>
</tbody>
</table>

Table 5.19 compares the two MCDM methods for ranking the projects and forming the portfolios. The projects’ ranks within each project type are identical for the EHS and the
maintenance projects, while the ranks vary for the productivity projects. While projects’ ranks vary in the productivity projects, the portfolios include the same projects using both MCDM methods.

The required budget is $128 million for productivity projects, $631.5 million for EHS projects, and $170.7 million for maintenance projects. These budgets are below the allocated budget ceiling for each project type given in Table 5.14. Consequently, the total required budget is $930.2 million, which is below the budget ceiling ($1000 million). The selected projects from the list of candidate projects are shaded gray in Table 5.19.

Table 5.19. Prioritized and Selected Projects in Different Project Types Using Two Various MCDM

<table>
<thead>
<tr>
<th>Productivity Projects</th>
<th>EHS Projects</th>
<th>Maintenance Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rank</td>
<td>PROMETHEE</td>
<td>AHP</td>
</tr>
<tr>
<td>1</td>
<td>P_{11}</td>
<td>P_{15}</td>
</tr>
<tr>
<td>2</td>
<td>P_{15}</td>
<td>P_{11}</td>
</tr>
<tr>
<td>3</td>
<td>P_{2}</td>
<td>P_{2}</td>
</tr>
<tr>
<td>4</td>
<td>P_{3}</td>
<td>P_{17}</td>
</tr>
<tr>
<td>5</td>
<td>P_{17}</td>
<td>P_{3}</td>
</tr>
<tr>
<td>6</td>
<td>P_{14}</td>
<td>P_{14}</td>
</tr>
<tr>
<td>7</td>
<td>P_{6}</td>
<td>P_{6}</td>
</tr>
<tr>
<td>8</td>
<td>P_{5}</td>
<td>P_{16}</td>
</tr>
<tr>
<td>9</td>
<td>P_{5}</td>
<td>P_{5}</td>
</tr>
</tbody>
</table>

The use of available budget would be less efficient when several portfolios should be formed because total budgets would not be allocated to portfolios. In fact, some part of budgets will remain unallocated for each portfolio.
In Case II, when projects are prioritized by their types, the projects’ ranks in PROMETHEE and AHP do not vary significantly. The case study shows that the maximum variation in projects’ ranks is just one unit. For example, P_3 and P_{17} are ranked four and five in PROMETHEE while in AHP, their ranks are reversed. All other projects have precisely the same ranks in both MCDM methods.

In Case I, the projects’ ranks vary considerably comparing PROMETHEE and AHP (Table 5.9). Except for the top three projects that have exactly the same ranking, other projects’ ranks changes one to five units. For example, P_3 has rank six in PROMETHEE while its rank is 11 in AHP.

5.3.2.4. **Probabilistic Analysis of Projects’ Ranks Using Ex-PROMETHEE**

The candidate projects were selected using deterministic criteria. In reality, some of the criteria have imprecise associated values and can best be modeled using probabilistic distributions. This section examines projects’ ranks with probabilistic criteria using Ex-PROMETHEE in conjunction with @Risk. Case II is considered for probabilistic analysis. Productivity and maintenance projects should be checked to select projects that are better aligned with organizational goals with high certainty. All EHS projects are selected because these projects have high priority in ABC Corporation, so probabilistic analysis is not required for these projects.

The boxplots in Figure 5.27 present the net flow variation of productivity projects. Three criteria (NPV, IRR, and ROI) are considered to have normal distributions with mean values equal to the values given in Table 5.11 and standard deviations (SD) equal to 10% of
means. P₁₁, P₁₅, P₂, P₃, and P₁₇ do not have overlap so considering the budget ceiling of $147.4 million for productivity projects, only P₁₁, P₁₅, and P₂ can be selected with high certainty that these projects are best aligned with organizational goals. In fact, the three probabilistic criteria do not alter the rank of these projects.

Figure 5.27. The Net Flow Variation of Productivity Project (SD = 10% mean)

Figure 5.28 indicates that there is no overlap between P₃ and P₁₇. However, P₃ may not be selected due to its required budget ($300 million), P₁₇ also will never be selected as it does not have overlap with P₂. The robustness of P₂ rank is because of the values of NPV and pioneer product (37526 and Yes) with weights of 3 and 4 in comparison to P₃ values (6000 and No). NPV has a V-shape preference function with p value equal to 2000. This means that P₂ gets the full credit for NPV and similarly for pioneer product. In contrast,
P₃ gets half credit from IRR and full credit from ROI. The values of IRR and ROI are 71.6 and 9.9 for P₃ versus 37.5 and 6.3 for P₂; however, the weights of IRR and ROI are 2.

![Figure 5.28](image.png)

Figure 5.28. The Probabilistic Distribution of Net Flow for P₂ and P₃ (SD = 10% mean)

Increasing the standard deviation of the three criteria gives similar results. Figure 5.29 illustrates the net flow variation of productivity projects when the standard deviation is 50% of the mean. There is no overlap between P₂ and P₃ (Figure 5.30) so P₁₇ will never be selected instead of P₂. In this case, P₁₁, P₁₅, and P₂ are selected with 100% certainty that other projects are not better.
Figure 5.29. The Net Flow Variation of Productivity Projects (SD = 50% mean)

Figure 5.30. The Probabilistic Distribution of Net Flow for $P_2$ and $P_3$ (SD = 50% mean)
Similar analysis can be fulfilled for maintenance projects to select projects that are better aligned with organizational goals. NPV may have probabilistic distribution among three preferred criteria. A normal distribution with mean values is given in Table 5.13, and SD is equal to 10% of the mean. The net flow variation of five candidate projects is shown in Figure 5.31. The boxplots indicate that candidate projects do not have overlap, so P_7 and P_1 are selected with 100% certainty because the required budget of P_{10} ($511.1 million) is over the budget ceiling ($221.1 million). The rank of P_1 is robustly above P_9 due to the values of safety risk and NPV. P_1 has safety risk and NPV values of M (medium) and 2177 with weights of 5 and 3 respectively while P_9 has values of L (low) and 510 for these criteria. However, P_9 criticality score is higher than P_1 (9 vs. 6), the weight of this criterion is 1, which is the minimum weight compared with two other criteria.

![Figure 5.31. The Net Flow Variation of Maintenance Projects (SD = 10% mean)](image)

Figure 5.31. The Net Flow Variation of Maintenance Projects (SD = 10% mean)
If SD increases to 30% of the mean, candidate projects’ boxplots would have overlap (Figure 3.32). The overlap between P₁ and P₉ should be investigated to understand the probability of their ranks’ exchange. Figure 5.33 illustrates that for 95% of the P₁ values, the probability that P₉ rank exchanges with P₁ is 0.7%, which is an ignorable number. P₁ rank is dominantly above P₉, and in this case, the selected projects are still P₇ and P₁.

Figure 5.32. The Net Flow Variation of Maintenance Projects (SD = 30% mean)
If the probabilistic distribution of projects’ net outranking flow values have overlap with high probability, the number of preferred criteria can be increased in order to easily distinguish projects’ ranks.

5.3.3. Case III: Prioritizing Projects based on Project Type with Balanced Budget on Portfolio Categories

The last case considers allocating budget among portfolio categories at the top of portfolio hierarchy instead of project types at the bottom of portfolio hierarchy. Top managers make budget decisions when budget is allocated among top level portfolio categories. All ABC Corporation’s sites send their candidate projects to the main portfolio management office. The candidate projects should be assigned to their own portfolio
categories. Projects will be prioritized and selected based on budget ceilings for each top level portfolio categories. Figure 5.34 indicates different steps that should be taken in this case.

Budget allocation in Case III is top-bottom. This means that when the required budgets on different portfolio categories are allocated, the budget for each portfolio category will be broken down into project types. An example of the portfolio categories in this case study is shown in Figure 5.1. Initially the required budget at the top portfolios should be allocated. The next level of portfolio hierarchy is the sites. According to the number and size of projects in different sites, the amount of budget for each portfolio should be allocated. Eventually, each site divides up the budget among different portfolio categories based on the weights of different project types. When the required budget is allocated to all the portfolio hierarchy levels, the projects can be selected for each of the portfolios considering their priority.
The case study is not suitable for this case because all projects belong to one site. The site includes different project types and is a subsidiary of plastics portfolio shown in Figure 5.1. It was not possible to gather information from other sites because the sites are dispersed all around the world. Moreover, there are confidentiality issues with this information gathering.
5.4. Balanced Risk on Portfolios

The quantitative and qualitative risk factor calculations were described in Chapter 3. In order to show the application of risk factors to the portfolio formation, we had to assign hypothetical values for risk factors to the projects in this case study. Given the ABC Corporation’s objectives, all EHS projects should be selected, so the risk factor does not have influence on this portfolio. The risk factors are considered for two other portfolios, which are productivity and maintenance. The assumed values of risk factors are listed in Tables 5.20 and 5.21 for productivity and maintenance project portfolios, respectively.

Table 5.20. Projects’ Risk Factors in Productivity Bucket

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Ideal Project</th>
<th>IRR (%)</th>
<th>NPV ($ million)</th>
<th>Pioneer Product</th>
<th>ROI-10 yrs</th>
<th>Risk Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max.</td>
<td>Max.</td>
<td>Yes</td>
<td>Max.</td>
<td>Min.</td>
</tr>
<tr>
<td>P_2</td>
<td></td>
<td>37.5</td>
<td>37526.00</td>
<td>Y</td>
<td>6.3</td>
<td>0.55</td>
</tr>
<tr>
<td>P_3</td>
<td></td>
<td>71.6</td>
<td>6000.00</td>
<td>N</td>
<td>9.9</td>
<td>0.10</td>
</tr>
<tr>
<td>P_5</td>
<td></td>
<td>25.3</td>
<td>1095.00</td>
<td>N</td>
<td>1.5</td>
<td>0.07</td>
</tr>
<tr>
<td>P_6</td>
<td></td>
<td>76.9</td>
<td>840.00</td>
<td>N</td>
<td>3.1</td>
<td>0.49</td>
</tr>
<tr>
<td>P_11</td>
<td></td>
<td>425.0</td>
<td>10293.00</td>
<td>Y</td>
<td>55.0</td>
<td>0.38</td>
</tr>
<tr>
<td>P_14</td>
<td></td>
<td>70.6</td>
<td>1950.00</td>
<td>N</td>
<td>11.9</td>
<td>0.21</td>
</tr>
<tr>
<td>P_15</td>
<td></td>
<td>41.7</td>
<td>72503.00</td>
<td>Y</td>
<td>6.6</td>
<td>0.37</td>
</tr>
<tr>
<td>P_16</td>
<td></td>
<td>50.0</td>
<td>2000.00</td>
<td>N</td>
<td>1.8</td>
<td>0.16</td>
</tr>
<tr>
<td>P_17</td>
<td></td>
<td>929.0</td>
<td>2012.59</td>
<td>N</td>
<td>6.4</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Table 5.21. Projects’ Risk Factors in Maintenance Bucket

<table>
<thead>
<tr>
<th>Criteria</th>
<th>NPV ($ million)</th>
<th>Safety Risk</th>
<th>Criticality Score</th>
<th>Risk Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal Project</td>
<td>Max.</td>
<td>High</td>
<td>Max.</td>
<td>Min.</td>
</tr>
<tr>
<td>P₁</td>
<td>2177.00</td>
<td>M</td>
<td>6.0</td>
<td>0.31</td>
</tr>
<tr>
<td>P₄</td>
<td>618.00</td>
<td>L</td>
<td>2.0</td>
<td>0.17</td>
</tr>
<tr>
<td>P₇</td>
<td>59938.00</td>
<td>L</td>
<td>7.0</td>
<td>0.50</td>
</tr>
<tr>
<td>P₉</td>
<td>510.00</td>
<td>L</td>
<td>9.0</td>
<td>0.12</td>
</tr>
<tr>
<td>P₁₀</td>
<td>5432.00</td>
<td>M</td>
<td>3.0</td>
<td>0.40</td>
</tr>
</tbody>
</table>

As a reminder, the risk factor was defined as a quantitative value to show the risk level of not only portfolios but also projects and programs (for detailed explanations refer to Section 3.3 of Chapter 3). Considering the information given in Table 5.20 for the productivity projects, PROMTHEE is used to optimize the selection of projects considering the limited budget. The level preference function is used for the risk factor (Figure A4.3).

The boundary value q is equal to one-third of difference between the maximum and minimum values of risk factors. In one portfolio, projects have various risk factors that the minimum and maximum of risk factors are used to calculate q. The other boundary value p is two thirds of this difference. The level preference function is selected based on the assumption that a risk factor less than one-third of the difference between maximum and minimum values does not influence the projects’ ranks. Sensitivity analysis should be performed on the risk factor to understand the effect of the risk factor’s weights in optimizing the selection of projects. Figure 5.35 indicates the results of sensitivity analysis on different risk factors’ weights and its effect on the projects’ ranks. The weights vary
from 1 to 11 compared to other criteria’s weights on the x-axis. Projects’ ranks are shown on the y-axis in Figure 5.35. P_5 and P_6 exchange their ranks for weight 3; P_{14} and P_{17} exchange their ranks for weight 5; P_2, P_3, P_{16}, and P_6 exchange their ranks for weight 6; and finally P_{14} and P_2 exchange their ranks for weight 11. The projects’ ranks remain unchanged for weights above 11 up to 20.

![Figure 5.35. Sensitivity Analysis on Risk Factor’s Weight on the Rank of Productivity Projects](image)

In Table 5.22, the selected projects are listed for various weights of the risk factor for productivity projects. The projects are selected considering the $147.4 million budget ceiling. Other criteria have constant weights when changing the weight of the risk factor. The selected projects are shown for each weight of the risk factor.
Table 5.22. Selected Productivity Projects for Various Risk Factor’s Weights

<table>
<thead>
<tr>
<th>Weight of Risk Factor</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected Projects</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
<td>P_2</td>
</tr>
<tr>
<td></td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
<td>P_{11}</td>
</tr>
<tr>
<td></td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
<td>P_{15}</td>
</tr>
</tbody>
</table>

It is apparent that the selected projects remain the same when the weight of the risk factor changes up to 10. When the weight is 11, P_{14} is selected instead of P_2. This means that an extremely risk-averse organization selects P_{14} instead of P_2. In this case study, the sensitivity analysis has been done for weights up to 20, and similar results are obtained for weights above 11. If the selected projects vary for different weights, the organization should decide about a suitable weight based on previous experience. Similar analysis can be conducted for the maintenance projects. Figure 5.36 shows the projects’ ranks for each risk factor’s weight.

![Figure 5.36. Sensitivity Analysis on Risk Factor’s Weight on the Rank of Maintenance Projects](image)

In Table 5.23, the selected projects are listed for each weight considering the $221.1 million budget ceiling. The weights of other criteria are constant when changing the risk
factor’s weight. Even though projects’ ranks vary for various weights of the risk factor (Table 5.23), the selected projects do not change significantly due to budget ceiling.

Table 5.23. Selected Maintenance Projects for Various Risk Factor’s Weights

<table>
<thead>
<tr>
<th>Weight of Risk Factor</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected Projects</td>
<td>P₁</td>
<td>P₁</td>
<td>P₄</td>
<td>P₄</td>
<td>P₄</td>
<td>P₄</td>
<td>P₄</td>
<td>P₄</td>
<td>P₄</td>
<td>P₄</td>
<td>P₄</td>
</tr>
<tr>
<td></td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
<td>P₇</td>
</tr>
<tr>
<td></td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
<td>P₉</td>
</tr>
</tbody>
</table>

A risk-prone organization selects P₁ and P₇ to be included in the maintenance project portfolio while a risk-averse organization substitutes P₄ and P₉ instead of P₁. The selected projects are identical for weights above 11 up to 20.

Using risk factor in the project ranking process helps to form balanced portfolios. These portfolios are balanced considering organizational goals. This means that forming portfolios by selecting those projects that are aligned with organizational goals to be risk-averse or risk-prone. P₁ and P₇ are selected to form the portfolios without risk factor, but the level of risk was ambiguous when selecting these projects. The risk factor assists to select P₄ and P₉ instead of P₁ in a risk-averse organization. In this way, the balanced portfolios are formed wisely considering organizational goals to be risk-prone or risk-averse.
5.5. Conclusions

PROMETHEE and AHP are two applicable MCDM methods to rank projects. The results of their applications in project portfolio formation are compared in this chapter. PROMETHEE has all the capabilities of AHP; in addition, it is flexible in defining different criteria’s preference functions and setting the preference function’s boundaries.

The two methods may give different results when different project types are included in one portfolio to be ranked. Those projects that have higher values on most of their criteria have similar ranks in both of the methods. Other projects that don’t have criteria with higher values have variable ranks. The projects’ ranks also depend on their preference functions in PROMETHEE, so selecting appropriate preference functions based on the organizational goals is important.

The two methods provide identical results when project types are separated in different portfolios and fewer projects are available in a portfolio. This conclusion cannot be generalized because if alternatives have close values for various criteria, then these methods give different results. Having similar project types in one portfolio, the preferred criteria for all the alternatives are identical, and all the alternatives have values for their preferred criteria. When all the project types are in one bucket with a set of preferred criteria, PROMETHEE and AHP give different ranks for projects. However, the top priority project is identical in both methods if its criteria are higher in comparison to other projects.

The risk factor inclusion in the project portfolio formation highlights the importance of risks from the first step of project portfolio management. All the risks at different
managerial levels are summarized in one risk factor that is used to create balanced portfolios. The sensitivity analysis on risk factor facilitates the formation of high and low risk portfolios. Organizations based on their strategy select projects to be somewhere on the spectrum from risk-prone to risk-averse.

The probabilistic analysis of input variables is essential to make sure the selected projects would not change by any expected changes of input variables. The Ex-PROMETHEE in conjunction with @Risk helps best to identify any exchange in projects’ ranks when the input variables have probabilistic distributions. The amount of overlap between candidate projects can be identified, and if the overlap is high, projects’ ranks may be exchanged with high probability. In this case, more criteria may be added to the list of preferred criteria.
Chapter 6 : Conclusions and Future Work

6.1. Conclusions

The application of project portfolio management (PPM) is growing in organizations in an effort to achieve their goals while using limited resources efficiently to survive in their highly competitive business lines. Six major reasons were identified by the comprehensive survey (CII IR303-2, 2014), and these reasons highlight the necessity of implementing PPM in organizations:

1. Enterprise-level objectives and goals
2. Consistency in processes
3. Group similar projects
4. Resource management
5. Owner versus contractor
6. Additional layer of management

A systematic project portfolio formation framework is essential for organizations to achieve three major goals: 1) Meet strategic objectives, 2) maximize the value of their portfolios, and 3) create a balance in terms of risks, business lines, and project types.
The comprehensive survey on PPM showed that two of the main areas that organizations would like to see improvements in are project portfolio formation and project prioritization. The portfolio formation is one of the major steps in effective PPM as attested by numerous academic and industry publications. Despite this, portfolio formation has not been formalized within owner organizations involved in the construction industry.

In this dissertation, a breakthrough framework is designed for portfolio formation using a hybrid of multicriteria decision-making (MCDM) methods that can be customized and implemented in all types of owner organizations. This framework contemplates the three major goals of project portfolio formation mentioned previously. This hybrid framework has six major steps. First, create balance in terms of business lines and project types by dividing up the restricted budget among different portfolios. If business lines are balanced, the budget allocation is top-down in the portfolio hierarchy, and if project types are balanced, the budget allocation is bottom-up. Both business lines and project types are different portfolio categories at the top levels of portfolio hierarchy or at the low level, respectively. Second, group projects in various project types and business lines considering portfolio hierarchy. Third, rank projects within a portfolio category using multiple preferred criteria including a risk factor. Projects’ risk factors are calculated in this step to be used in prioritizing candidate projects. Fourth, create balance in terms of risks in portfolios considering organizational risk tolerance level. This step requires a sensitivity analysis on the risk factor’s weight to rank projects for each risk factor’s weight. Fifth, select the top value projects under a budget constraint. Considering the sensitivity
analysis, the selected projects have high risks when the risk factor’s weight is low and the opposite because the ideal value of risk factor is minimal. This means that projects with lower risk factors will be given higher values, and when the risk factor’s weight increases, the ranks of projects with lower risk factors escalate. Sixth, check the interdependencies among projects to avoid selecting succeeding projects without their preceding projects.

Two MCDM methods are used to implement the designed framework. MCDM methods allow the consideration of several criteria, some of which conflict with others, to rank projects as part of the project portfolio formation framework. PROMETHEE is identified as a proper method for ranking projects compared to AHP due to several reasons. First, PROMETHEE is more flexible in terms of using preference functions and defining restrictions on criteria. PROMETHEE gives the flexibility to use six different preference functions for each criterion. Second, projects’ ranks and selected projects are more consistent using PROMETHEE when all candidate projects are included in one portfolio or in various portfolios. This idea is demonstrated in the case study as well as other studies.

A new method is suggested to convert qualitative evaluation of global risks to a quantitative risk factor. AHP is an appropriate method to convert qualitative risks to a quantitative risk factor based on the RBS of a portfolio. This application of AHP is new, and it is designed based on other applications of AHP identified in the literature review.

In this method, a risk breakdown structure (RBS) for a portfolio should be considered including all the risks at various levels of RBS hierarchy to reflect risks at organization, portfolio, program, and project levels. Then, projects’ risks should be evaluated qualitatively and then converted to quantitative values using a Likert scale. AHP can be
used to calculate a quantitative risk factor based on quantitative risks on the RBS, which looks like a hierarchy. Therefore, the developed framework uses a hybrid of PROMETHEE and AHP to form balanced portfolios.

The quantitative risk factor is included in the process of ranking projects for the first time. The risk factor plus other criteria are considered to select those projects that give the highest value to an organization. Risks are included in this process because of their importance in various businesses. This helps organizations to include risks from the initial phases of portfolio management. Moreover, the proposed framework is designed to avoid any favoritism in selecting and forming project portfolios that happen in public organizations. This framework assists organizations in forming their portfolios following a systematic procedure while it has flexibility to be customized.

Projects’ risk factors are considered in the designed framework to not only rank projects but also create a balanced portfolio in terms of risks. Organizations decide on the composition of their portfolios based on their risk tolerance or appetite. The balanced portfolio is defined based on the organizational risk tolerance level from risk-prone to risk-averse.

Projects’ ranks vary by changing the number of preferred criteria. Even though criteria have some interrelation, the strength of correlation between two criteria varies from one project to another. This means that considering more than one criterion in one area such as finance does not lead to double counting if weights are decided based on criteria areas and then divide each area’s weight among its various criteria. More criteria in the project
ranking process increase the accuracy of projects’ ranks. The criteria’s weights in one area should be decided considering organizational goals.

In real conditions, the input variables and criteria’s weights may have probabilistic distributions to rank projects. The projects’ ranks should be analyzed to select a robust list of projects. The Ex-PROMETHEE tool, which is based on PROMETHEE implemented on an Excel worksheet, is developed to do probabilistic analysis when this tool is used in conjunction with @Risk. This tool has limitation in the number of preferred criteria and alternatives. It could include up to 10 alternatives and 20 criteria. The variation of the projects’ net outranking flows can be identified to analyze the probability of exchanging projects’ ranks, which can change the list of selected projects. If the list of selected projects changes considering the probabilistic input variables, one solution is to include more preferred criteria in ranking projects. The other solution is to select precise distributions for probabilistic input variables.

A Matlab code is developed for AHP without any restrictions on the number of alternatives and criteria. This code helps to avoid numerous calculations required in AHP to evaluate projects’ ranks, and it checks the consistency of pairwise comparison matrix of criteria.

The interdependencies among projects are checked in the last step of portfolio formation framework. An interdependency tree among projects is designed, and based on that a flowchart is developed to check all the interdependencies included in the tree. This step prevents selecting projects dependent on other projects. This helps to make sure the selected projects create value for an organization based on the economic analysis. This
step can be eliminated by including the interdependent projects in one program and calculating the preferred criteria for the program. In this case, programs will be ranked with other independent projects, and if their priorities are high, they may be selected considering restricted budget to form portfolios.

6.2. Future Work

Project portfolio formation is affected by many criteria with uncertainties. To make wise decisions in selecting projects and forming portfolios, the most relevant criteria should be selected, and the weight of each criterion should be decided to give the desired results. Furthermore, uncertainties should be accounted for in the project portfolio formation. Probabilistic analysis of criteria is important for project prioritization to identify any variations in projects’ ranks and to select those projects that are best aligned with organizational goals.

The designed portfolio formation framework is made of several steps or modules that are considered separately. One module is to rank projects, one is to create balance in portfolios in terms of risks, and another is to check the interdependencies among projects. A development in the designed portfolio formation framework can be made by merging two modules: 1) Creating balance in portfolios in terms of risks and 2) checking interdependencies among projects, into the ranking projects step. This means that by defining other criteria, in the process of ranking projects, creates balanced portfolios in terms of risks and avoids selecting projects without their interdependent projects. One criterion can be related to creating balance in portfolios in terms of risks, and another
criterion is to check the interdependencies. The selected projects create balance in terms of risks based on the organizational risk tolerance level and do not have interdependency issues. In fact, the projects will be prioritized considering all their interdependencies. In this way, the ranking project step (module) includes the other two modules, and a MCDM method can be used to select the high value projects, which create balanced portfolios in terms of risks and don’t have interdependency issues.

The designed Ex-PROMETHEE can be used in decision making problems when there are 20 criteria and 10 alternatives. A further development in the Ex-PROMETHEE can help to use it as an open source for probabilistic analysis of projects’ ranks without any restrictions on the number of alternatives and criteria. Furthermore, the designed AHP Matlab code is an open source that can be advanced using other Matlab capabilities. This advancement is for developing a package for probabilistic analysis of input variables, such as risk factors or even weights. In addition, the Matlab code can be further developed to include other MCDM methods such as PROMETHEE, TOPSIS, and VICOR. In this way, the outputs of various MCDM methods can be compared in one snapshot.

The comprehensive survey on PPM showed that the criteria for project prioritization and selection vary from organization to organization. Standardizing the criteria for different industries helps to select the most valuable projects out of the list of candidate projects. A catalog of the most relevant criteria in different industries assists an organization to choose criteria efficiently.

The other factor that helps industries to implement project portfolio formation easier is criteria’s weights. However, the survey among heavy industry organizations showed that
they do not have similar criteria’s weights to prioritize projects; average weights help industries to have an impression in this field. Making a broad survey on this subject helps other organizations to realistically implement the project portfolio formation in their organizations. Of course, organizations should modify their weights based on their goals over time.

Industry is looking for an effective and convenient way of forming portfolios using a minimum amount of resources. The proposed project portfolio formation framework requires a thorough understanding of the business, MCDM methods, and risk management that can be included in a code. This code should include all the steps of the portfolio formation framework to create balanced portfolios following organizational goals. The input variables are portfolio categories, project types, portfolio hierarchy levels, criteria values, criteria’s weights, qualitative or qualitative risks, and budget ceilings. The code output is the list of project portfolios including optimized selected projects aligned with organizational goals.

The application of PPM is developing fast in organizations to use their limited resources efficiently. Portfolio formation is one of the major initial phases in the PPM. The developed framework helps organizations to increase the probability of success in their highly competitive businesses. The mechanization of the developed framework increases its application that leads to more prosperous organizations.
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Appendix 1: Finalized Survey Questions

Northeastern University, Georgia Institute of Technology and University of Florida are conducting this survey on behalf of the Construction Industry Institute (CII). We are gathering information from a number of firms regarding the management of a Portfolio of projects. The objective of the research is to develop a set of best practices that can be used to improve Portfolio management throughout the construction industry.

In this survey, a portfolio is defined as a group of related or unrelated projects and/or programs managed by a single individual, hereafter referred to as a portfolio manager.

Your input is very important to us as it will help us to document and assess current industry practices for managing a group of projects. It can also be helpful to identify potential best practices for Portfolio management.

We would appreciate if you could forward this survey to Portfolio managers within your firm. Thank you for your assistance.

Sincerely,

Dr. Ali Touran, Northeastern University
Principal Investigator

The information collected from you will remain strictly confidential, and your name or other identifying information will not appear on any survey reports. Only aggregate data will be analyzed and reported. Should you require any assistance in completing the survey, please contact Dr. Ali Touran (Phone: (617-373-5508, Email: A.Touran@neu.edu).
**Firm Info**

1. Your firm’s name .................................................................................................................................................. 

2. Your name ............................................................................................................................................................

3. Your role:
   - Project Manager
   - Program Manager
   - Portfolio Manager
   - Project Director
   - Project Controls Manager
   - Other................................................................................................................................................................ (please specify)

4. Is your firm a member of the Construction Industry Institute?
   - Yes
   - No

5. Do you consider your firm to be ... 
   - Owner
   - Contractor/Consultant
   - Other................................................................................................................................................................ (please specify)

6. Which industry sectors is your firm active in?
   - Infrastructure
   - Building (Non-residential)
   - Heavy Industry (Chemical MFG, Electrical (Generating), Gas Distribution, Environmental, Metals Refining/Processing, Mining, Natural Gas Processing, Oil Exploration/Production, Oil Refining, Oil Sands Mining/Extraction, Oil Sands SAGD, Oil Sands Upgrading, Cogeneration, Pulp and Paper, Others.)
• Light Industry (Automotive MFG, Consumer Products Manufacturing, Foods, Microelectronics Manufacturing, Office Products Manufacturing, Pharmaceutical Manufacturing, Pharmaceutical Labs, and Clean Room.)
• Other ...........................................................................................................................................(please specify)

**Makeup of a Portfolio**

7. Does your firm have individuals who manage a group of projects simultaneously?
   • Yes
   • No

8. If the answer to previous question is “No,” please explain WHY.

9. If answer to question seven is “Yes,” what is the title of the individuals who manage a group of projects? (Select all that apply)
   • Project Manager
   • Program Manager
   • Portfolio Manager
   • Project Director
   • Other ...........................................................................................................................................(please specify)

10. Typically, how many projects are managed in a Portfolio?
    • Less than 6
    • 6 to 10
    • 11 to 20
    • 21 to 50
    • More than 50

11. What is the typical total budget for a Portfolio that an individual manages?
    • Less than $5M
• $5M to $10M
• $10M to $25M
• $25M to $50M
• $50M to $100M
• More than $100M

12. What is the typical duration of projects that are included in a Portfolio?
   • Less than 6 months
   • six to 12 months
   • 12 to 24 months
   • More than 24 months

**Current practices**

13. In what areas is your firm using tools, techniques and processes that are tailored to manage a group of projects at a Portfolio level? (Select all that apply)
   • Schedule
   • Cost
   • Cash flow
   • Procurement
   • Resource Allocation
   • Communication
   • Quality
   • Scope
   • Change Management
   • Safety
   • Risk Management
   • Issue Management
   • None
   • Other......................................................................................................................................................(please specify)
14. Has your firm implemented any innovative practices or procedures in Portfolio management? (Please comment.)

15. What standard or customized tools (commercial or custom-built software), techniques and processes does your firm use to manage a group of projects at a Portfolio level? (Please provide the name and briefly describe the usage for each area.)
   - Schedule ........................................................................................................................................
   - Cost ................................................................................................................................................
   - Cash flow ....................................................................................................................................... 
   - Procurement .................................................................................................................................
   - Resource Allocation ....................................................................................................................
   - Communication ...........................................................................................................................
   - Quality ...........................................................................................................................................
   - Scope ..............................................................................................................................................
   - Change Management ....................................................................................................................
   - Safety .............................................................................................................................................
   - Risk Management ...........................................................................................................................
   - Issue Management .......................................................................................................................... 
   - None (Insert “None” in the box) .....................................................................................................
   - Other ............................................................................................................................................... (please specify)

16. Please list any tools, techniques and processes under development to manage a group of projects at a Portfolio level in your firm.

17. Has your firm had any success at adapting the CII best practices, tools, techniques, and processes to manage a group of projects at the Portfolio level?
   - Yes, please explain............................................................................................................................
   - No (Insert “No” in the box) ...........................................................................................................
18. In what areas does the Portfolio manager have authorization to share or allocate resources among the projects? (Select all that apply)

- Budget
- Work force
- Procurement strategy
- Sequence of execution (Schedule adjustment)
- None
- Other..............................................................................................................(please specify)

19. Does your firm use any formal system to prioritize projects in a Portfolio?

- Yes, please explain........................................................................................................
- No (Insert “No” in the box) .........................................................................................

Performance Metrics

20. Does your firm use any metrics to measure and monitor performance of projects at the Portfolio level?

- Yes
- No

21. If the answer to previous question is “Yes,” in what areas is your firm using metrics for measuring performance of projects at the Portfolio level? (Select all that apply and describe)

- Schedule .....................................................................................................................
- Cost ..............................................................................................................................
- Cash flow ...................................................................................................................
- Procurement ..............................................................................................................
- Resource Allocation .................................................................................................
- Communication ......................................................................................................
- Quality .......................................................................................................................


• Scope .................................................................................................................................
• Change Management ......................................................................................................
• Safety .............................................................................................................................
• Risk Management .........................................................................................................
• Issue Management ........................................................................................................
• Key Performance Indicators (KPI) ....................................................................................
• None (Insert “None” in the box) .....................................................................................
• Other ..............................................................................................................................(please specify)

22. In what areas does your firm need to improve metrics at the Portfolio level? (Select all that apply)
• Schedule
• Cost
• Cash flow
• Procurement
• Resource Allocation
• Communication
• Quality
• Scope
• Change Management
• Safety
• Risk Management
• Issue Management
• Key Performance Indicators (KPI)
• None
• Other ..............................................................................................................................(please specify)
23. Does your firm use a scorecard/dashboard to show the performance of a Portfolio?
   - Yes
   - No

24. If answer to the above question is “Yes,” in what areas are metrics included in the scorecard/dashboard? What are these metrics?
   - Schedule
   - Cost
   - Cash flow
   - Procurement
   - Resource Allocation
   - Communication
   - Quality
   - Scope
   - Change Management
   - Safety
   - Risk Management
   - Issue Management
   - Key Performance Indicators (KPI)
   - Overall Portfolio health
   - Success
   - Other (please specify)

25. On a scale of 1 (least important) to 5 (most important), how would you describe the importance of the following areas in an ideal score card/dashboard for managing a project portfolio? (Please select one number for each area.)
   - Schedule
   - Cost
   - Cash flow
- Procurement
- Resource Allocation
- Communication
- Quality
- Scope
- Change Management
- Safety
- Risk Management
- Issue Management
- Key Performance Indicators (KPI)
- Overall Portfolio health
- Success

**Implementation**

26. How successful is Portfolio management in your firm?

- 5 (Best in Class)
- 4 (Very)
- 3 (Average)
- 2 (Somewhat)
- 1 (Not at All)
- Don’t know

27. What are or have been the barriers to the successful application of Portfolio management in your firm? (If applicable, please give brief explanation for your selections.)

- Lack of industry standards, best practices and available training
- Unclear objectives and priorities
- Lack of common code structure
- Cost of implementation (Software, etc.)
• Lack of management support or direction..............................................................
• Management interference (Micro-management)......................................................
• Lack of awareness of value added...........................................................................
• Lack of previous success........................................................................................
• Other....................................................................................................................(please specify)

28. We appreciate your time in completing this survey. As this is a part of ongoing research for improving Portfolio management, please provide any additional suggestions and comments that you have.
Appendix 2: Questionnaire to Identify the Weights of Various Project Types for Allocating Budget and Weights of Criteria for Ranking Projects

Dear Sir / Madam,

This is a brief follow-up survey to an online survey on portfolio management that you generously participated in last year. This survey gathers experts’ ideas and views about how organizations allocate budget for their portfolios, different portfolio types available in an organization, weight of each portfolio type, criteria to rank projects in different portfolio types, and weight of those criteria.

Your input is crucial to me because it will help to document and assess the current construction industry practices for portfolio formation. The result of this survey will be used in a PhD dissertation on portfolio formation and will be shared as a courtesy.

Your assistance is greatly appreciated. Should you require any assistance in completing the survey, please contact Mr. Reza Masoumi (Phone: 617-373-3991, Email: r.masoumi@neu.edu).

Best Regards,

Reza Masoumi
PhD Student at Northeastern University
Civil and Environmental Eng. Department

The information collected from you will remain strictly confidential, and your name or other identifying information will not appear on any survey reports. Only aggregate data will be analyzed and reported.
1. Which of the following industrial sectors best describes your organization? (Please select all that apply.)

☐ Infrastructure
☐ Building
☐ Heavy Industrial
☐ Light Industrial
☐ Other

2. Which budgeting approach does your organization follow for portfolio hierarchy? (In the bottom-up approach the portfolio budget is summed up from the bottom of portfolio hierarchy to the top portfolio level considering each project budget. In the top-down approach, the total organization budget based on organization’s goals is allocated to top portfolios and then broken down the portfolio hierarchy until the portfolio budget is fully allocated.)

☐ Bottom-up
☐ Top-down

3. Which of the following portfolio types do you have in your organization?

☐ Productivity projects (to lower cost; improve productivity and quality)
☐ Environmental, Health, and Safety (EHS) projects
☐ Maintenance projects
☐ Strategic projects (to increase sales/revenue; increase capacity; expansion)
☐ R&D
☐ Others (please explain):
   •
   •
   •
4. Please rank each portfolio type listed in table below from 1 (the most important) to 5 (the least important) with respect to budget allocation for portfolio management.

<table>
<thead>
<tr>
<th>Portfolio Type</th>
<th>1 Most Important</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 Least Important</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity projects (to lower cost; improve productivity and quality)</td>
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<tr>
<td>Environmental, Health, and Safety (EHS) projects</td>
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<tr>
<td>Maintenance projects</td>
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<tr>
<td>Strategic projects (to increase sales/revenue; increase capacity; expansion)</td>
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<tr>
<td>R&amp;D</td>
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<tr>
<td>Other project types (if any mentioned in question #3)</td>
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</tbody>
</table>

5. Please select the preferred criteria in your organization to rank projects within each portfolio type?

- Productivity projects (to lower cost; improve productivity and quality)
  - Payback period
  - NPV
  - IRR
  - Pioneer product
  - ROI
  - Other (please explain):
• **Environmental, Health, and Safety (EHS) projects**
  - ☐ Safety compliance
  - ☐ Safety risk
  - ☐ Amount of damages
  - ☐ Other (please explain):

• **Maintenance projects**
  - ☐ NPV (based on failure cost)
  - ☐ Criticality score
  - ☐ Safety risk
  - ☐ Other (please explain):

• **Strategic projects (to increase sales/revenue; increase capacity; expansion)**
  - ☐ Alignment to business strategy
  - ☐ NPV
  - ☐ IRR
  - ☐ Pioneer product
  - ☐ ROI
  - ☐ Other (please explain):

• **R&D**
  - ☐ Alignment to business strategy
  - ☐ NPV
  - ☐ IRR
  - ☐ Pioneer product

• **Other project types (if any mentioned in question #3)**
6. Please rank the preferred criteria in your organization selected in question 5 for each portfolio type from 1 (the most important) to 5 (the least important).

<table>
<thead>
<tr>
<th>Productivity projects (to lower cost; improve productivity and quality)</th>
<th>1 Most Important</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5 Least Important</th>
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<tbody>
<tr>
<td>• Payback period</td>
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<td>• NPV</td>
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<td>• IRR</td>
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<td>• Pioneer Product</td>
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<td>• ROI</td>
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<td>• Other (if any mentioned in question #5)</td>
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<th>Environmental, Health, and Safety (EHS) projects</th>
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<th>4</th>
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<td>• Safety compliance</td>
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<td>• Other (if any mentioned in question #5)</td>
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<tr>
<th>Maintenance projects</th>
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<th>3</th>
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<th>5 Least Important</th>
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</thead>
<tbody>
<tr>
<td>• NPV (based on failure cost)</td>
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<td>• Criticality score</td>
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<th>Strategic projects (to increase sales/revenue; increase capacity; expansion)</th>
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Appendix 3: Matlab Code to Calculate Priority Vector

A3.1. Using Equivalent of Qualitative Risks

The following code is developed to calculate the priority vector, $\lambda_{max}$, consistency index (CI), and consistency ratio (CR) based on the equivalent quantitative values of qualitative risks. The first two parts of the code is for data entering, and all the calculations are done in Part 3.

```matlab
%**********************************************************************
*****
clear all
clc
---

m = input('Number of candidate projects(m)= '); %------Part 2------Part 2------Part 2------Part 2------Part 2------
---

%%% Enter the equivalent of qualitative risks to calculate the pairwise
comparison risk matrix of candidate projects (C) %%%%
str='""""Enter the equivalent of qualitative risks """"';
disp(str)
for i=1:m
    str = ['Number of candidate project: ', num2str(i)];
disp(str)
    ww(i) = input('What is the equivalent quantitative value of qualitative risk? ');%------Part 3------Part 3------Part 3------Part 3------Part 3------
---

%%% Calculate the priority vector for equivalent qualitative risk matrix
C & maximum eigenvalue and CIc and CRC %%%%

for j=1:m
    CSC(j)=sum(C(:,j));%------Part 3------Part 3------Part 3------Part 3------Part 3------
---

for i=1:m
    SC(i,j)=C(i,j)/CSC(j);
end
```
end
for j=1:m
    PVc(j,1)=mean(SC(j,:));
end
PVc
%%% Calculate the maximum eigenvalue of risk matrix (LMc), CIc, and CRc of C %%%
PVL=zeros(m,1);
for j=1:m
    PVL=PVL(j,1)*C(:,j)+PVL;
end
for j=1:m
    LV(j,1)=PVL(j,1)/PVc(j,1);
end
LMc=mean(LV);str=['LMc = ', num2str(LMc)];disp(str)
CIc=(LMc-m)/(m-1);str=['CIc = ', num2str(CIc)];disp(str)
if m <= 2
    RI=0;str=['RI=0 and CRc=CIc/RI can not be calculated!'];disp(str)
elseif m == 3
    RI=.52;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 4
    RI=.89;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 5
    RI=1.11;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 6
    RI=1.25;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 7
    RI=1.35;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 8
    RI=1.4;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 9
    RI=1.45;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 10
    RI=1.49;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 11
    RI=1.51;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 12
    RI=1.48;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 13
    RI=1.56;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 14
    RI=1.57;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m == 15
    RI=1.59;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m > 15
    str=['The number of alternatives is out of range!'];disp(str)
end
%***********************************************************************
*****%
A3.2. Using Pairwise Comparison of Risks

The following code can be used when the equivalent quantitative pairwise comparison risk matrix of qualitative pairwise comparison risk matrix is available. The code is used to calculate the priority vector, \( \lambda_{\text{max}} \), CI, and CR.

```matlab
%**********************************************************************
****
clear all
clc
%1------%
m = input('Number of candidate projects (m) = ');
%------Part 2------Part 2------Part 2------Part 2------Part 2------
%2------%
%% Enter the equivalent quantitative pairwise comparison risk matrix C
%% of qualitative pairwise comparison risk matrix %%%%
str = ['"""Enter the elements of equivalent quantitative pairwise comparison risk matrix C including the pairwise comparison of
criteria"""
';
for j = 1:m
    str = [str ',num2str(j),',']
end
str = [str ')']
disp(str)
for j = 1:m
    for i = 1:m
        str = ['(i,j) = (', num2str(i),',',num2str(j),')']
        disp(str)
        C(i,j) = input('Enter the pairwise comparison of risk i to j = ');
    end
end
C;
%------Part 3------Part 3------Part 3------Part 3------Part 3------
%3------%
%% Calculate the priority vector of pairwise comparison risk matrix C
%% & maximum eigenvalue and CIc and CRc %%%%
for j = 1:m
    CSC(j) = sum(C(:,j));
    for i = 1:m
        SC(i,j) = C(i,j)/CSC(j);
    end
end
for j = 1:m
    PVc(j,1) = mean(SC(j,:));
end
PVc
%% Calculate the maximum eigenvalue (LMc), CIc, and CRc of C %%%%
PVL = zeros(m,1);
for j = 1:m
    PVL = PVc(j,1)*C(:,j) + PVL;
end
```
for j=1:m
    LV(j,1)=PVL(j,1)/PVc(j,1);
end
LMc=mean(LV);str=['LMc = ', num2str(LMc)];disp(str)
CIc=(LMc-m)/(m-1);str=['CIc = ', num2str(CIc)];disp(str)
if m <= 2
    RI=0;str=['RI=0 and CRc=CIc/RI can not be calculated!'];disp(str)
elseif m==3
    RI=.52;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==4
    RI=.89;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==5
    RI=1.11;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==6
    RI=1.25;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==7
    RI=1.35;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==8
    RI=1.4;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==9
    RI=1.45;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==10
    RI=1.49;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==11
    RI=1.51;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==12
    RI=1.48;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==13
    RI=1.56;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==14
    RI=1.57;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==15
    RI=1.59;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m > 15
    str=['The number of alternatives is out of range!'];disp(str)
end

%**********************************************************************
*****%
Appendix 4: Detailed PROMETHEE and AHP Methodologies

A4.1. PROMETHEE Methodology

A MCDM method is required when there are several alternatives to be evaluated and alternatives have several preferred criteria. PROMETHEE makes it possible to include the knowledge and opinions of an expert group in the process of decision-making. This method is explained in this section for ranking and selecting alternatives which best align with preferred criteria. PROMETHEE I and II will initially be solved parametrically, and then a real example is solved both manually and using the software to compare the results.

The parametric PROMETHEE is used to develop Ex-PROMETHEE. The parametric PROMETHEE includes the following characteristics:

- n alternatives \( (a_i, i = 1 .. n) \)
- k preferred criteria \( (C_j, j = 1 .. k) \)
- R decision makers (DM) \( (r = 1 .. R) \)
- \( r^{th} \) decision maker gives weight to criteria \( (w_{jr}) \) \( (j = 1 .. k \text{ & } r = 1 .. R) \)
- Decision makers have different weights \( (\omega_r) \) \( (r = 1 .. R) \)

PROMETHEE I and II methods can be completed in three stages with 11 steps (Machartis et al., 1998). The difference between I and II is explained later in this chapter. The majority of steps should be done in the first stage called “Preliminary”. In stage 2, decision makers evaluate alternatives individually, and the global decision based on the consensus of
decision makers will be handled in stage 3. The stages and their related steps are illustrated in Figure A4.1.

**A4.1.1. Stage 1: Preliminary**

It is assumed that steps 1 through 6 in Figure A4.1 are covered, and the list of “n” alternatives and “k” preferred criteria have been identified. Based on the gathered information, the matrix can be formed including the values of criteria for different alternatives, preference functions, and weights of criteria.

“A” is a vector which includes the set of n alternatives. Each criterion is shown by $f_j(.)$ for $j = 1, 2, \ldots, j, \ldots, k$ illustrated in Table A4.1.
A = \begin{bmatrix} a \\ b \\ \vdots \\ i \\ \vdots \\ n \end{bmatrix} \quad \text{(A4.1)}

Table A4.1. Description of \( f_j(.) \) for \( j = 1, 2, \ldots, j, \ldots, k \)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>( f_1(.) )</th>
<th>( f_2(.) )</th>
<th>( \vdots )</th>
<th>( f_j(.) )</th>
<th>( \vdots )</th>
<th>( f_k(.) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>( f_1(a) )</td>
<td>( f_2(a) )</td>
<td>( \vdots )</td>
<td>( f_j(a) )</td>
<td>( \vdots )</td>
<td>( f_k(a) )</td>
</tr>
<tr>
<td>b</td>
<td>( f_1(b) )</td>
<td>( f_2(b) )</td>
<td>( \vdots )</td>
<td>( f_j(b) )</td>
<td>( \vdots )</td>
<td>( f_k(b) )</td>
</tr>
<tr>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>i</td>
<td>( f_1(i) )</td>
<td>( f_2(i) )</td>
<td>( \vdots )</td>
<td>( f_j(i) )</td>
<td>( \vdots )</td>
<td>( f_k(i) )</td>
</tr>
<tr>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>n</td>
<td>( f_1(n) )</td>
<td>( f_2(n) )</td>
<td>( \vdots )</td>
<td>( f_j(n) )</td>
<td>( \vdots )</td>
<td>( f_k(n) )</td>
</tr>
</tbody>
</table>

The values of criteria for different alternatives can be arranged in a table similar to Table A4.2. The \( f_1(a) \) means the value of criterion one for alternative “a” and generally \( f_j(i) \) means the value of criterion \( j \) for \( i \)th alternative.
A4.1.1.1. Weights of Criteria

The importance of criteria is evaluated by defining their weights, which can be determined using a variety of methods (Eckerode, 1965; Nijkamp et al., 1990; Saaty and Vargas, 2001.) It is required to define the weights of criteria according to step 7 in Figure A4.1. The sum of the weights should be equal to one. The weights of criteria is \( w_j \), \( j = 1, 2, \ldots, k \). Overall, each decision maker should adopt \( k \) weights. For \( r^{th} \) decision maker:

\[
\sum_{j=1}^{k} w_j^r = 1
\]  

(A4.2)

A4.1.1.2. Preference Function

The preference function illustrates how pairwise evaluation differences are transformed into values of preference. In fact, the preference function translates the difference between the values of two criteria into a preference degree in the range of 0 to 1 (Macharis et al., 2004). On the other hand, the preference function allows translating the deviations observed on a specific criterion into degrees of preference independent of its scale. Step 8, which is the last step in stage 1, requires defining the preference functions for all criteria.

If \( P_j \) is a preference function associated with \( j^{th} \) criterion \( f_j(.) \), then:

\[
P_j(a, b) = G_j[f_j(a) - f_j(b)] , \quad 0 \leq P_j(a, b) \leq 1
\]  

(A4.3)

\( a \) and \( b \): two independent alternatives
$G_j$ is a non-decreasing function of deviation between $f_j(a)$ and $f_j(b)$. If $f_j$ is a criterion to be maximized, then:

$$G_j[f_j(a) - f_j(b)] = 0 \quad \text{if} \quad f_j(a) < f_j(b) \quad \text{no preference}$$

$$G_j[f_j(a) - f_j(b)] \sim 0 \quad \text{if} \quad f_j(a) > f_j(b) \quad \text{weak preference}$$

$$G_j[f_j(a) - f_j(b)] = 1 \quad \text{if} \quad f_j(a) >> f_j(b) \quad \text{strict preference}$$

The difference between two alternatives on a specific criterion can be translated to degrees of preference independent of its scale as shown in Figure A4.2.

![Figure A4.2. Preference Function (Macharis et al., 1998)](image)

Six different preference functions are defined in PROMETHEE as shown in Figure A4.3 (Brans, 1982; Brans and Vincke, 1985; Brans et al., 1986; Brans and Mareschal, 1994).
Each of the preference functions can be defined using zero to two parameters. Usual preference function does not require any parameter because the preference is always equal to one; U-Shape, V-Shape, and Gaussian have one parameter; Level and Linear (V-Shape with indifference criterion) have two parameters. These parameters define the shape of preference function. In Figure A4.3, parameter “d” is:

$$d = f_j(a) - f_j(b)$$  \hspace{1cm} (A4.5)

**a and b:** two independent alternatives

$$f_j(.):$$ values of criteria j for different alternatives

The thresholds in different preference functions are shown with maximum three parameters: “q”, “p”, and “s.” The “q” is the lower threshold or a threshold of indifference. In fact, “q” is the maximum value of “d” below which the decision maker considers indifference when comparing two alternatives. The “p” is the higher threshold or a threshold of strict preference. It is the minimum value of “d” above which the decision maker deems strict preference.
Gaussian function is defined using one parameter “s” which is recommended to consider the “q” and “p” and then set the “s” between them (Brans and Mareschal, 2005). The closer “s” is to “q,” the more preference increases for small deviation in difference of two criteria. The opposite is true when “s” is closer to “p” (Brans and Mareschal, 2005).
These functions and their thresholds define how the pairwise difference of each criterion will be evaluated. For example, if the preference function is Level with indifference and strict thresholds of 20 and 50, then the pairwise differences of criterion can be categorized into the following three categories if the criterion is supposed to be maximized:

- Difference of alternatives for a criterion is less than 20, the preference function is zero.
- Difference of alternatives for a criterion is between 20 and 50, the preference function is 0.5.
- Difference of alternatives for a criterion is higher than 50, the preference function is one.

For the cases that a criterion should be minimized, the preference functions in Figure A4.4 must be used while other formulas do not change. The preference functions in Figure A4.4 are suggested to simplify understanding of the manual calculations and in case of writing a code for PRTOMETHEE I and II. However, the values of “q”, “p,” and “s” should be considered positive when the minimization of a criterion is preferred. The negative sign of these parameters should be considered to calculate the preference function. For example, in the above example, if the criterion is supposed to be minimized and thresholds are kept unchanged:

- Difference of alternatives for a criterion is greater than -20, the preference function is zero.
- Difference of alternatives for a criterion is between -20 and -50, the preference function is 0.5.
- Difference of alternatives for a criterion is lower than -50, the preference function is one.

Figure A4.4. The Six Preference Functions for Minimum Criteria
The threshold(s) and types of preference functions can be fixed using the organizational experiences or strategies. For example, if one organization is active in a business line with usually high NPV projects, one of the Level, Linear, or U-shape preference functions can be selected to compare criteria. Organizational strategy is also important in selecting the preference function and its threshold(s). Sometimes organizations decide to enter into a new business line, even though the NPV of projects in that business is low.

A4.1.2. Stage 2: Individual PROMETHEE Analysis

PROMETHEE I and II are explained in this section when only one decision maker is engaged in the process of decision-making. In stage 2, PROMETHEE analysis will be completed in step 9, individual PROMETHEE analysis, depicted in Figure A4.1. When stage one is accomplished by recognizing a variety of alternatives, identifying the preferred criteria and their values for all alternatives, considering the weight of each criterion in comparison to others, and deciding the preference functions, then the analysis can start to calculate PROMETHEE I and II. All the required information to calculate PROMETHEE I and II from stage 1 is shown in Table A4.3.
Table A4.3. Evaluation Table (Macharis et al., 1998)

<table>
<thead>
<tr>
<th>Preference Function of Criteria</th>
<th>( P_1(\cdot,\cdot) )</th>
<th>( P_2(\cdot,\cdot) )</th>
<th>...</th>
<th>( P_j(\cdot,\cdot) )</th>
<th>...</th>
<th>( P_k(\cdot,\cdot) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights of Criteria</td>
<td>( w_1 )</td>
<td>( w_2 )</td>
<td>...</td>
<td>( w_j )</td>
<td>...</td>
<td>( w_k )</td>
</tr>
<tr>
<td>Alternatives</td>
<td>( f_1(\cdot) )</td>
<td>( f_2(\cdot) )</td>
<td>...</td>
<td>( f_j(\cdot) )</td>
<td>...</td>
<td>( f_k(\cdot) )</td>
</tr>
<tr>
<td>( a )</td>
<td>( f_1(a) )</td>
<td>( f_2(a) )</td>
<td>...</td>
<td>( f_j(a) )</td>
<td>...</td>
<td>( f_k(a) )</td>
</tr>
<tr>
<td>( b )</td>
<td>( f_1(b) )</td>
<td>( f_2(b) )</td>
<td>...</td>
<td>( f_j(b) )</td>
<td>...</td>
<td>( f_k(b) )</td>
</tr>
<tr>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \vdots )</td>
<td>( \ddots )</td>
<td>( \vdots )</td>
<td>( \ddots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>( i )</td>
<td>( f_1(i) )</td>
<td>( f_2(i) )</td>
<td>...</td>
<td>( f_j(i) )</td>
<td>...</td>
<td>( f_k(i) )</td>
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<td>( \vdots )</td>
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<td>( \vdots )</td>
<td>( \ddots )</td>
<td>( \vdots )</td>
<td>( \ddots )</td>
<td>( \vdots )</td>
</tr>
<tr>
<td>( n )</td>
<td>( f_1(n) )</td>
<td>( f_2(n) )</td>
<td>...</td>
<td>( f_j(n) )</td>
<td>...</td>
<td>( f_k(n) )</td>
</tr>
</tbody>
</table>

PROMETHEE I and II use the following equations for each decision maker (DM) (Brans and Mareschal, 1992, 1994, 2005; Macharis, 2004):

\[
\begin{cases}
\pi(a,b) = \frac{\sum_{j=1}^{k} P_j(a,b) \cdot w_j}{\sum_{j=1}^{k} w_j} \\
\text{if } \sum_{j=1}^{k} w_j = 1 \\
\end{cases}
\Rightarrow \pi(a,b) = \sum_{j=1}^{k} P_j(a,b) \cdot w_j \quad (A4.6)
\]

\[
\phi^+(a) = \frac{1}{n-1} \cdot \sum_{x \in A} \pi(a,x) \quad (A4.7)
\]

\[
\phi^-(a) = \frac{1}{n-1} \cdot \sum_{x \in A} \pi(x,a) \quad (A4.8)
\]

**a**: belongs to the set A of Alternatives

**\( \pi(a,b) \)**: preference index that shows with which degree a is preferred to b (arithmetic average of all the \( P_j(a,b) \) (j= 1, 2, ..., k) if all the criteria weights are equal)
\( \phi^+ (a) \): measures power of a positive outranking flow

\( \phi^- (a) \): measures weakness of a negative outranking flow

The positive outranking flow of alternative “a” expresses how much “a” is outranking all other alternatives (Figure A4.5). The higher \( \phi^+ \) is better because it represents the higher power of alternative “a”, its outranking character (Brans and Mareschal, 2005).

The negative outranking flow of alternative “a” expresses how much “a” is outranked by all other alternatives. The smaller \( \phi^- \) is better because it represents the lower weakness of alternative “a”, its outranked character.

![Diagram of outranking flows](image)

**Figure A4.5.** PROMETHEE Outranking Flow (Brans and Mareschal, 2005)

PROMETHEE I, which is partial ranking, uses both \( \phi^+ \) and \( \phi^- \) to illustrate the strength and weakness of each alternative. The values of \( \phi^+ \) and \( \phi^- \) are normalized to be between -1 and 1 by multiplying sum of the preference indexes of each alternative in comparison to others by \( \frac{1}{n-1} \). Outranking flows get values between -1 and 1. The positive and negative
outranking flow of two alternatives can be compared in the following ways by using terms: $P^+, P^-, I^+, I^-$.

\[
\begin{align*}
  & a \, P \, b \quad \text{iff} \quad \phi^+ (a) > \phi^+ (b) \\
  & a \, I^+ \, b \quad \text{iff} \quad \phi^+ (a) = \phi^+ (b) \\
\end{align*}
\]

(A4.9)

\[
\begin{align*}
  & a \, P^- \, b \quad \text{iff} \quad \phi^- (a) < \phi^- (b) \\
  & a \, I^- \, b \quad \text{iff} \quad \phi^- (a) = \phi^- (b) \\
\end{align*}
\]

(A4.10)

\( P \): Prefer
\( I \): Indifference

Considering the above comparisons for negative and positive outranking flow, the alternatives can be compared with each other accordingly using PROMETHEE I. Generally, alternatives can have three different statuses in comparison to each other (Brans et al., 1984; Brans and Vincke, 1985; Brans and Mareschal, 1994):

\[
\begin{align*}
  & a \, P^I \, b \quad \text{iff} \quad \begin{cases} 
  a \, P^+ \, b \quad \text{and} \\
  a \, I^+ \, b \quad \text{and} \\
  a \, I^- \, b \quad \text{and} \\
  a \, P^- \, b \\
  \end{cases} \\
  & a \, I^I \, b \quad \text{iff} \quad a \, I^+ \, b \quad \text{and} \quad a \, I^- \, b \\
  & a \, R \, b \quad \text{otherwise} \\
\end{align*}
\]

(A4.11)

\( a \, P^I \, b \): “\( a \)” is Preferred to “\( b \)”. In this case, alternative “\( a \)” has higher strength and lower weakness than “\( b \)”; therefore, certainly “\( a \)” is preferred to “\( b \)".
a I \ b: “a” and “b” are Indifferent. The negative and positive outranking flow of “a” and “b” are equal.

a R b: “a” and “b” are Incomparable. In this case, the higher power of alternative “a” is associated with the less weakness of alternative “b”. This is when one alternative has strength (better values) in a subset of criteria in which another one is weak and vice versa.

PROMETHEE II gives the complete ranking by subtracting $\phi^+$ and $\phi^-$. It is the net outranking flow and the higher the net flow, the better the alternative.

$$\phi(a) = \phi^+(a) - \phi^-(a)$$ (A4.12)

$\phi(a)$: value function net flow of alternative “a”

### A4.1.2.1. How to Calculate the Positive and Negative Outranking

The positive and negative outranking flows can be calculated expanding the given formula. The formulas are developed in this section to show precisely how the positive and negative outranking of alternative “a” can be calculated.

$$\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) = \frac{1}{n-1} [\pi(a, b) + ... + \pi(a, i) + ... + \pi(a, n)]$$ (A4.13)

and
\[ \pi(a,b) = \sum_{j=1}^{k} P_j(a,b) \cdot w_j \]  
(A4.14)

Therefore,

\[ \phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \sum_{j=1}^{k} P_j(a,x) \cdot w_j = \]

\[ = \frac{1}{n-1} \cdot \{ [P_1(a,b) \cdot w_1 + P_2(a,b) \cdot w_2 + \cdots + P_k(a,b) \cdot w_k] + \cdots + [P_1(a,n) \cdot w_1 + P_2(a,n) \cdot w_2 + \cdots + P_k(a,n) \cdot w_k] \} \]

(A4.15)

On the other hand the preference function is: \( P_j(a,b) = G_j \{ f_j(a) - f_j(b) \} \) then:

\[ \phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \sum_{j=1}^{k} P_j(a,x) \cdot w_j = \]

\[ = \frac{1}{n-1} \cdot \{ [G_1 \{ f_1(a) - f_1(b) \} \cdot w_1 + G_2 \{ f_2(a) - f_2(b) \} \cdot w_2 + \cdots + G_k \{ f_k(a) - f_k(b) \} \cdot w_k] + \cdots + [G_1 \{ f_1(a) - f_1(i) \} \cdot w_1 + G_2 \{ f_2(a) - f_2(i) \} \cdot w_2 + \cdots + G_k \{ f_k(a) - f_k(i) \} \cdot w_k] + \cdots + [G_1 \{ f_1(a) - f_1(n) \} \cdot w_1 + G_2 \{ f_2(a) - f_2(n) \} \cdot w_2 + \cdots + G_k \{ f_k(a) - f_k(n) \} \cdot w_k] \} \]

(A4.16)

The negative outranking flow can be calculated using the given formula for alternative \( a \).

The expanded formula is shown in equation A4.17.
The calculations described above can be tabulated like Table A4.4.

\[
\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) = (A4.18)
\]

Table A4.4. Calculation of Preference Index for Alternative “a”

<table>
<thead>
<tr>
<th>Preference Function</th>
<th>( P_1(\cdot, \cdot) )</th>
<th>( \ldots )</th>
<th>( P_j(\cdot, \cdot) )</th>
<th>( \ldots )</th>
<th>( P_k(\cdot, \cdot) )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weights</strong></td>
<td>( w_1 )</td>
<td>( \ldots )</td>
<td>( w_j )</td>
<td>( \ldots )</td>
<td>( w_k )</td>
</tr>
<tr>
<td><strong>Criteria</strong></td>
<td>( f_1(\cdot) )</td>
<td>( \ldots )</td>
<td>( f_j(\cdot) )</td>
<td>( \ldots )</td>
<td>( f_k(\cdot) )</td>
</tr>
<tr>
<td><strong>Alternative</strong></td>
<td>( a )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
<td>( \ldots )</td>
</tr>
<tr>
<td></td>
<td>( G_1[f_1(a)-f_1(b)] )</td>
<td>( \ldots )</td>
<td>( G_j[f_j(a)-f_j(b)] )</td>
<td>( \ldots )</td>
<td>( G_k[f_k(a)-f_k(b)] )</td>
</tr>
<tr>
<td></td>
<td>( \cdot w_1 )</td>
<td>( \ldots )</td>
<td>( \cdot w_j )</td>
<td>( \ldots )</td>
<td>( \cdot w_k )</td>
</tr>
<tr>
<td></td>
<td>( \pi(a, b) )</td>
<td>( \ldots )</td>
<td>( \pi(a, i) )</td>
<td>( \ldots )</td>
<td>( \pi(a, n) )</td>
</tr>
</tbody>
</table>
The preference index for alternative “b” is shown in Table A4.5. The only difference between Tables A4.4 and A4.5 is that alternative “a” should change to “b” and the opposite.

\[
\phi^+(b) = \frac{1}{n-1} \sum_{x \in A} \pi(b, x)
\]  

(A4.19)

Table A4.5. Calculation of Preference Index for Alternative “b”

<table>
<thead>
<tr>
<th>Preference Function</th>
<th>Preference Function</th>
<th>Preference Function</th>
<th>Preference Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_1(\cdot, \cdot) )</td>
<td>( P_2(\cdot, \cdot) )</td>
<td>( P_j(\cdot, \cdot) )</td>
<td>( P_k(\cdot, \cdot) )</td>
</tr>
<tr>
<td>( w_1 )</td>
<td>( w_2 )</td>
<td>( w_j )</td>
<td>( w_k )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Criteria</th>
<th>Criteria</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1(\cdot) )</td>
<td>( f_2(\cdot) )</td>
<td>( f_j(\cdot) )</td>
<td>( f_k(\cdot) )</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
G_1[f_1(b)-f_1(a)] \cdot w_1 &+ \ldots + G_j[f_j(b)-f_j(a)] \cdot w_j &+ \ldots + G_k[f_k(b)-f_k(a)] \cdot w_k &= \pi(b, a) \\
G_1[f_1(b)-f_1(i)] \cdot w_1 &+ \ldots + G_j[f_j(b)-f_j(i)] \cdot w_j &+ \ldots + G_k[f_k(b)-f_k(i)] \cdot w_k &= \pi(b, i) \\
G_1[f_1(b)-f_1(n)] \cdot w_1 &+ \ldots + G_j[f_j(b)-f_j(n)] \cdot w_j &+ \ldots + G_k[f_k(b)-f_k(n)] \cdot w_k &= \pi(b, n)
\end{align*}
\]

The preference indices for all the alternatives can be calculated similarly. Having all the preference indices facilitates the creation of the preference index \( \pi \) matrix, which is an n-by-n matrix shown in Table A4.6. The sum of each row multiplied by \( \frac{1}{n-1} \) of the preference index matrix gives \( \phi^+ \) related to that alternative while the sum of each column multiplied by \( \frac{1}{n-1} \) gives \( \phi^- \) related to that alternative.
Table A4.6. The Preference Index (π) Matrix

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>...</th>
<th>i</th>
<th>...</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>-π(a,b)</td>
<td>π(a,i)</td>
<td>π(a,n)</td>
<td>φ⁺(a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>π(b,a)</td>
<td>-π(b,i)</td>
<td>π(b,n)</td>
<td>φ⁺(b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>⋱</td>
<td>⋱</td>
<td>⋱</td>
<td>⋱</td>
<td>⋱</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>π(i,a)</td>
<td>π(i,b)</td>
<td>-</td>
<td>π(i,n)</td>
<td>φ⁺(i)</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>⋱</td>
<td>⋱</td>
<td>⋱</td>
<td>⋱</td>
<td>⋱</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>π(n,a)</td>
<td>π(n,b)</td>
<td>π(n,i)</td>
<td>-</td>
<td>φ⁺(n)</td>
<td></td>
</tr>
</tbody>
</table>

φ⁻(a) φ⁻(b) ⋱ φ⁻(i) ⋱ φ⁻(n)

A4.1.3. Stage 3: Global Evaluation

It is recommended that major decisions in an organization be made by a group of experts to avoid any bias in the process of decision-making. The collective decision-making does not depend on type of organization, which may be public or private, national or international (Dyer et al., 1992). Several studies have been conducted in the field of group decision-making using different MCDM methods (Lai et al., 2002; Saaty, 2004).

In global evaluation, it is assumed that there are R decision makers in the process of decision-making. The formulas given in stage 2 should be modified to include the ideas of various decision makers autonomously.

The net flow formula for global evaluation will be calculated using the values of net flow from each decision maker. Index r is used in the formulas to indicate the r\textsuperscript{th} decision maker in calculating the global net flow for each alternative. The formula to calculate the net flow for a group of R decision makers is given below (Macharis et al., 1998):

Taking equation A4.2 into account:
\[
\begin{aligned}
\pi^r(a, b) &= \frac{\sum_{j=1}^{k} P_j(a, b) \cdot w_j^r}{\sum_{j=1}^{k} w_j^r} \\
\text{if } \sum_{j=1}^{k} w_j^r &= 1 \\
\rightarrow \pi^r(a, b) &= \sum_{j=1}^{k} P_j(a, b) \cdot w_j^r \quad \text{(A4.20)}
\end{aligned}
\]

\[
\phi^+(a) = -\frac{1}{n-1} \sum_{x \in A} \pi^r(a, x) \quad \text{(A4.21)}
\]

\[
\phi^-(a) = -\frac{1}{n-1} \sum_{x \in A} \pi^r(x, a) \quad \text{(A4.22)}
\]

\[
\phi^r(a) = -\frac{1}{n-1} \phi^+(a) - \phi^-(a) \quad \text{(A4.23)}
\]

The decision makers usually are at different levels of an organization. The importance of decision makers can be considered using weight factors. If \( \omega_r \) is the weight factor or relative importance of \( r^{th} \) decision maker, then:

\[
\omega_1, \omega_2, \ldots, \omega_r, \ldots, \omega_R \quad \text{and} \quad \sum_{r=1}^{R} \omega_r = 1 \quad \text{(A4.24)}
\]

Considering all of the decision makers, the generalized net flow matrix can be formed including the net flow of alternatives based on each decision maker. The process of global decision-making is shown schematically in Figure A4.6 from individual decision maker to global evaluation.
Having the relative importance of decision makers, $\omega_r$, and net flows based on the individual evaluation, the global net flow of each alternative can be calculated by:

$$\phi^G(a_i) = \sum_{r=1}^{R} \phi^r(a_i) \cdot \omega_r$$  \hspace{2cm} (A4.25)

**A4.2. AHP Methodology**

Analytical hierarchy process (AHP) includes both rational and intuitive thinking to choose the best alternative with respect to several criteria. It helps decision makers to describe the decision by decomposing a complex problem into levels of hierarchy including objectives, criteria, sub-criteria, and alternatives. It is based on pairwise comparison judgments which are used to rank the alternatives. Three steps can be considered for AHP (Holguin-Veras, 1995):

1. The definition of the hierarchy
2. The comparison among criteria
3. The weighting and adding process
AHP starts gathering information for different criteria related to each alternative. Alternatives have some quantitative or qualitative criteria. The quantitative criteria are based on facts and figures or physical measurements while the qualitative criteria are evaluated by expertise. AHP requires changing all the criteria to quantitative values. In the case of having qualitative criteria, AHP uses the nine scales shown in Table A4.7 (Saaty and Vargas, 2012) or Likert scale (Al-Harbi, 2001) with the proper number of scales (Matell, 1972). The scale varies from 1 (equal importance) to 9 (extreme importance). The next step is to compare the alternatives for each criterion and form the so-called pairwise comparison matrix. Comparing criteria for alternatives can be done using ratio scale judgment, which is calculated based on relative or pairwise comparison $a_{ij}$ of alternatives for each criterion.

### Table A4.7. The Fundamental Scale (Saaty and Vargas, 2012)

<table>
<thead>
<tr>
<th>Intensity of importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>Two activities contribute equally to the objective</td>
</tr>
<tr>
<td>2</td>
<td>Weak</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
<td>Experience and judgment slightly favor one activity over another</td>
</tr>
<tr>
<td>4</td>
<td>Moderate plus</td>
<td>Experience and judgment favor one activity over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
<td>Experience and judgment strongly favor one activity over another</td>
</tr>
<tr>
<td>6</td>
<td>Strong plus</td>
<td>An activity is favored very strongly over another; its dominance demonstrated in practice</td>
</tr>
<tr>
<td>7</td>
<td>Very strong or demonstrated importance</td>
<td>The evidence favoring one activity over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>8</td>
<td>Very, very strong</td>
<td>A reasonable assumption</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td>A reasonable assumption</td>
</tr>
</tbody>
</table>

| Reciprocals of above    | If activity $i$ has one of the above nonzero numbers assigned to it when compared with activity $j$, then $j$ has the reciprocal value when compared with $i$ |
| Rationals               | Ratios arising from the scale | If consistency were to be forced by obtaining $n$ numerical values to span the matrix |
The decision-making problem is to rank “n” candidate alternatives using qualitative or quantitative criteria. The “n” alternatives are evaluated based on “m” criteria. The pairwise comparison of alternatives will be considered for all the criteria. It means that for each criterion an n-by-n matrix can be calculated by pairwise comparison of alternatives. The pairwise comparison matrix $A_k$ for $k^{th}$ criteria is:

$$A_k = (a_{ij}^k) \quad i, j = 1, 2, \ldots, n \quad \text{and} \quad k = 1, 2, \ldots, m$$  \hspace{1cm} (A4.26)$$

$$a_{ij}^k = \frac{1}{a_{ji}^k} \quad \text{for all} \quad i, j \in A$$  \hspace{1cm} (A4.27)$$

$n$: number of alternatives

$m$: number of criteria

$k$: comparison matrix related to $k^{th}$ criteria

All the elements of $A_k$ can be calculated using the above formula:

$$A_k = \begin{bmatrix}
1 & a_{12}^k & \cdots & a_{1n}^k \\
\frac{1}{a_{12}} & 1 & \cdots & a_{2n}^k \\
\vdots & \vdots & \ddots & \vdots \\
\frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1
\end{bmatrix}$$  \hspace{1cm} (A4.28)$$
In reality, the pairwise comparison matrix for each criterion should be calculated based on the quantitative values of criteria. Considering quantitative values of “m” criteria for “n” alternatives in Table A4.8, the pairwise comparison matrix is calculated again:

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1</td>
</tr>
<tr>
<td>A1</td>
<td>W11</td>
</tr>
<tr>
<td>A2</td>
<td>W12</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>A_n</td>
<td>W1n</td>
</tr>
</tbody>
</table>

Considering the k\textsuperscript{th} criterion, the quantitative values of alternative i and j are w\textsubscript{ki} and w\textsubscript{kj}; then the element a\textsubscript{ij} of the matrix A\textsuperscript{k} can be calculated:

\[
a_{ij}^k = \frac{w_{ki}}{w_{kj}}
\]  

(A4.29)

Accordingly, the A\textsuperscript{k} can be formed using the values of criteria for different alternatives,

\[
A^k = \begin{bmatrix}
\frac{w_{k1}}{w_{k1}} & \frac{w_{k1}}{w_{k2}} & \cdots & \frac{w_{k1}}{w_{kn}} \\
\frac{w_{k2}}{w_{k1}} & \frac{w_{k2}}{w_{k2}} & \cdots & \frac{w_{k2}}{w_{kn}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{w_{kn}}{w_{k1}} & \frac{w_{kn}}{w_{k2}} & \cdots & \frac{w_{kn}}{w_{kn}}
\end{bmatrix}
= \begin{bmatrix}
1 & \frac{w_{k1}}{w_{k2}} & \cdots & \frac{w_{k1}}{w_{kn}} \\
\frac{w_{k2}}{w_{k2}} & 1 & \cdots & \frac{w_{k2}}{w_{kn}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{w_{kn}}{w_{k1}} & \frac{w_{kn}}{w_{k2}} & \cdots & 1
\end{bmatrix}
\]  

(A4.30)
Calculating $A^k$ based on the real values of criteria gives a pairwise comparison matrix with zero consistency index (CI). Otherwise, CI of the pairwise comparison matrix should be checked. The priority of alternatives and consistency check for each pairwise comparison matrix $A^k$ can be calculated using the eight step procedure below:

**Step 1:** Divide the numbers in each column of the pairwise comparison matrix by the summation of that column. The synthesized matrix is shown below for $A^k$:

$$
\begin{bmatrix}
1 & \frac{w_{k1}}{w_{k2}} + \frac{w_{k2}}{w_{k1}} + \cdots + \frac{w_{kn}}{w_{k1}} & \frac{w_{k1}}{w_{k2}} + 1 + \cdots + \frac{w_{kn}}{w_{k2}} & \cdots & \frac{w_{k1}}{w_{kn}} + \frac{w_{k2}}{w_{kn}} + \cdots + 1 \\
\frac{w_{k2}}{w_{k1}} & 1 & \frac{w_{k1}}{w_{k2}} + 1 + \cdots + \frac{w_{kn}}{w_{k2}} & \cdots & \frac{w_{k2}}{w_{kn}} + \frac{w_{k1}}{w_{kn}} + \cdots + 1 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
\frac{w_{kn}}{w_{k1}} & \frac{w_{kn}}{w_{k2}} & \cdots & 1 & \frac{w_{k1}}{w_{kn}} + \frac{w_{k2}}{w_{kn}} + \cdots + 1
\end{bmatrix}
$$

(A4.31)

**Step 2:** Calculate the average of each row to form the priority vector. The priority vector is calculated using the synthesized matrix values. The entities of priority vector are the average of each row.
Step 3: Calculate each criterion's weighted sum vector. This is the criterion's priority vector multiplied by each column of A. For example, the weighted sum vector of the $k^{th}$ criterion can be calculated using the related priority vector $PV_i^k$ multiplied by the $i^{th}$ column of $A^k$:
\[
\begin{bmatrix}
WS_1^k \\
WS_2^k \\
\vdots \\
WS_n^k
\end{bmatrix} = \begin{bmatrix}
W_{k1} \\
W_{k1} \\
\vdots \\
W_{kn}
\end{bmatrix} \cdot PV_1^k + \begin{bmatrix}
W_{k1} \\
W_{k2} \\
\vdots \\
W_{kn}
\end{bmatrix} \cdot PV_2^k + \ldots + \begin{bmatrix}
W_{k1} \\
W_{k2} \\
\vdots \\
W_{kn}
\end{bmatrix} \cdot PV_n^k =
\end{equation}

\[
WS_i^k = \sum_{j=1}^{n} PV_j^k \cdot \frac{w_{ki}}{w_{kj}}, \quad i = 1, 2, \ldots, n \quad \& \quad k = 1, 2, \ldots, m \tag{A4.33}
\]

**Step 4:** Divide all the criteria weighted sum matrices by their respective priority vector.

\[
\frac{WS_1^k}{PV_1^k}, \frac{WS_2^k}{PV_2^k}, \ldots, \frac{WS_n^k}{PV_n^k} \tag{A4.34}
\]

**Step 5:** Calculate the maximum eigenvector by averaging the numbers in Step 4.

\[
\lambda_{max}^k = \frac{\sum_{i=1}^{n} \frac{WS_i^k}{PV_i^k}}{n} = \frac{\lambda_{max}^k}{n} \tag{A4.35}
\]

**Step 6:** Calculate CI and then consistency ratio (CR). If CR is less than 0.1, the level of consistency is acceptable; otherwise, revise the judgment and consequently change the pairwise comparison matrix.
AHP allows inconsistency on input variables such as weights of criteria due to using the experts’ judgments. Ghavamifar (2009) highlighted that the pairwise comparison matrix for the importance of criteria has inconsistency due to evaluation by the decision makers and AHP. CR essentially should be checked when one criterion is evaluated based on experts’ judgments rather than objective measurements. Experts should modify their judgments if CR is out of the permissible range. CR is supposed to be less than 0.1 (Saaty and Vargas, 2012); otherwise, the experts’ judgments should be revised to decrease CR to less than 0.1.

The CI for the \( k \)th criterion can be calculated with following formula:

\[
CI^k = \frac{\lambda_k^{\text{max}} - n}{(n-1)}
\]  

(A4.36)

CR can be calculated by comparing the CI with the random consistency index (RI) which can be calculated using Table A4.9 (Saaty and Vargas, 2012). Each of the average random consistency indices shown in Table A4.9 is an average random consistency index derived from a sample of arbitrarily generated reciprocal matrices using the scale 1/9, 1/8, ..., 1, ..., 8, 9.

\[
CR = \frac{CI}{RI}
\]  

(A4.37)
Table A4.9. Average Random Consistency Index (RI) (Saaty and Tran, 2007)

<table>
<thead>
<tr>
<th>Size of Matrix</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random</td>
<td>0</td>
<td>0</td>
<td>0.52</td>
<td>0.89</td>
<td>1.11</td>
<td>1.25</td>
<td>1.35</td>
<td>1.4</td>
<td>1.45</td>
<td>1.49</td>
<td>1.51</td>
<td>1.48</td>
<td>1.56</td>
<td>1.57</td>
<td>1.59</td>
</tr>
<tr>
<td>Consistency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Index (RI)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Step 7:** Repeat all the steps for all the pairwise comparison matrices including the pairwise comparison matrix for the importance of criteria. When all the elements of the hierarchy including criteria, sub-criteria, and alternatives have priority vector with acceptable CR, the priority of each alternative can be calculated in step 8.

**Step 8:** Determine the priority of each alternative according to the calculated priority vectors (Figure A4.7).

\[
\text{Overall Priority of Alternative 1} = \sum_{i=1}^{m} PV_{C_1} \cdot PV_{1}^{i} = PV_{C_1} \cdot PV_{1}^{1} + PV_{C_2} \cdot PV_{1}^{2} + \ldots + PV_{C_m} \cdot PV_{1}^{m}
\]

\[
\text{Overall Priority of Alternative 2} = \sum_{i=1}^{m} PV_{C_1} \cdot PV_{2}^{i} = PV_{C_1} \cdot PV_{2}^{1} + PV_{C_2} \cdot PV_{2}^{2} + \ldots + PV_{C_m} \cdot PV_{2}^{m}
\]

\[
\vdots
\]

\[
\text{Overall Priority of Alternative n} = \sum_{i=1}^{m} PV_{C_1} \cdot PV_{n}^{i} = PV_{C_1} \cdot PV_{n}^{1} + PV_{C_2} \cdot PV_{n}^{2} + \ldots + PV_{C_m} \cdot PV_{n}^{m}
\]

(A4.38)
AHP Example

Solving an actual example manually helps to understand AHP procedure. A typical example is buying a new car; four various manufacturers (n = 4) are among the alternatives, i.e., Ford, Toyota, Honda, and Hyundai. The question is which car meets the buyer’s needs best considering buyer’s all preferred criteria. The first step is to collect the required information for all cars regarding each criterion. The preferred criteria are considered to be “Price,” “Fuel Consumption,” “Power,” “Guarantee Period,” “Trunk Volume,” and “Finance Rate” (m = 6). All the alternatives should have similar units for each criterion. In this example, all the criteria are assumed to have similar weights. This assumption is not close to reality, but as different people have various tastes and ideas, similar weights are considered for all the criteria.

The ideal value for criteria can be minimum or maximum. If the ideal value of a criterion is the minimum value, then the minimum value among alternatives for that criterion is
more favorable and vice versa. This example has two criteria with minimum ideal value which are “Price” and “Finance Rate.”

Table A4.10 depicts the quantitative values of different criteria for all the alternatives. Alternative 4 and 3 have the highest value among alternatives on criteria 1 and 6 respectively, which have minimum ideal values. Other criteria have maximum ideal value. The values of alternatives 3, 1, 4, and 4 have the highest value for criteria 2, 3, 4, and 5, respectively.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternatives</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Ford Focus 4dr Sdn SE</td>
<td>18,615</td>
<td>27</td>
<td>160</td>
<td>3</td>
<td>13.2</td>
<td>2.90</td>
</tr>
<tr>
<td>Toyota Corolla 4dr Sdn CVT S Plus SE</td>
<td>19,700</td>
<td>29</td>
<td>132</td>
<td>3</td>
<td>13</td>
<td>3.86</td>
</tr>
<tr>
<td>Honda Civic Sdn 4dr CVT LX</td>
<td>19,190</td>
<td>30</td>
<td>143</td>
<td>3</td>
<td>12.5</td>
<td>1.90</td>
</tr>
<tr>
<td>Hyundai Elantra 4dr Sdn Auto SE</td>
<td>18,200</td>
<td>28</td>
<td>145</td>
<td>5</td>
<td>14.8</td>
<td>3.90</td>
</tr>
</tbody>
</table>
Having the required information for alternatives, the pairwise comparison of criteria should be identified. This usually happens by the experts’ judgments. The process of pairwise comparison of criteria can be accomplished in a meeting session. The experts give their ideas individually and then discuss to reach a consensus. Table A4.12 shows an individual preference evaluation on pairwise comparison of criteria using five-point Likert scale defined in Table A4.11. Saaty and Vargas (2012) proposed a full nine scales of intensity of importance while Cheung et al. (2005) used five points to define the fuzzy numbers for importance.

Table A4.11. Five-Point Likert Scale

<table>
<thead>
<tr>
<th>Equal Importance</th>
<th>Weak Importance</th>
<th>Strong Importance</th>
<th>Very Strong Importance</th>
<th>Extreme Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

The “Price” and “Fuel Consumption” are considered to be more important than other criteria while the trunk volume is deemed to have the least importance shown in Table A6.3.
Table A4.12. Pairwise Comparison of Six Criteria

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Price ($)</td>
<td>Fuel Consumption (mpg)</td>
<td>Power (hp)</td>
<td>Guarantee Period (yrs)</td>
<td>Trunk Volume (ft³)</td>
<td>Finance Rate (%)</td>
</tr>
<tr>
<td>1</td>
<td>Price</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Fuel Consumption</td>
<td>1/3</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Power</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Guarantee Period</td>
<td>1/5</td>
<td>1/5</td>
<td>1/5</td>
<td>1</td>
<td>7</td>
<td>1/3</td>
</tr>
<tr>
<td>5</td>
<td>Trunk Volume</td>
<td>1/9</td>
<td>1/9</td>
<td>1/7</td>
<td>1/7</td>
<td>1</td>
<td>1/7</td>
</tr>
<tr>
<td>6</td>
<td>Finance Rate</td>
<td>1/5</td>
<td>1/5</td>
<td>1/3</td>
<td>3</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>

Table A4.12 helps to form the pairwise comparison matrix for criteria $A_c$.

$$A_c = \begin{bmatrix} 1 & 3 & 3 & 5 & 9 & 5 \\ 1/3 & 1 & 3 & 5 & 9 & 5 \\ 1/3 & 1 & 1 & 5 & 7 & 3 \\ 1/5 & 1/5 & 1 & 7 & 1 & 3 \\ 1/9 & 1/9 & 1/7 & 1 & 1 & 7 \\ 1/5 & 1/5 & 3 & 7 & 1 & 1 \end{bmatrix}$$
The pairwise comparison matrix of criteria gives $\lambda_{\text{max}} = 6.746$ and $\text{CR} = 0.120$. The new judgment on the importance of criteria is required because the priority vector of the initial $A_C$ is greater than 0.1.

$$\begin{bmatrix}
0.384 \\
0.264 \\
0.166 \\
0.068 \\
0.023 \\
0.096
\end{bmatrix}$$

The revised judgment is given in Table A4.13. Except the “Price,” some of the weights of all other criteria have altered to decrease the value of CR to less than 0.1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price ($)</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Fuel Consumption (mpg)</td>
<td>$\frac{1}{3}$</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Power (hp)</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Guarantee Period (yrs)</td>
<td>$\frac{1}{5}$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>1</td>
<td>3</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>Trunk Volume (ft³)</td>
<td>$\frac{1}{9}$</td>
<td>$\frac{1}{7}$</td>
<td>$\frac{1}{7}$</td>
<td>$\frac{1}{3}$</td>
<td>1</td>
<td>$\frac{1}{7}$</td>
</tr>
<tr>
<td>Finance Rate (%)</td>
<td>$\frac{1}{5}$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>3</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>
The revised pairwise comparison matrix of the importance of criteria gives \( \lambda_{\text{max}} = 6.468 \) and \( CR = 0.075 \); therefore, the new importance of criteria is acceptable because \( CR \) is less than 0.1. The priority vector of \( A_C \) is:

\[
P_{VC} = \begin{bmatrix}
0.403 \\
0.229 \\
0.165 \\
0.063 \\
0.027 \\
0.114
\end{bmatrix}
\]

The next step is to generate the relative comparison matrix \( A^k (k = 1, 2, \ldots, m) \) for each criterion. Obviously, \( CR \) for all the criteria is zero because the pairwise comparison matrix is formed using the quantitative values of criteria rather than judgment. All calculations are required to have the comparison matrix of two criteria, “Price” and “Fuel Consumption,” based on the quantitative values of criteria. The details of calculations are not shown for other criteria and just the results of calculations are demonstrated. Considering the price criterion, the comparison matrix \( A^1 \) is parametrically shown:

\[
A^1 = \begin{bmatrix}
a_{11}^1 & a_{12}^1 & a_{13}^1 & a_{14}^1 \\
a_{21}^1 & a_{22}^1 & a_{23}^1 & a_{24}^1 \\
a_{31}^1 & a_{32}^1 & a_{33}^1 & a_{34}^1 \\
a_{41}^1 & a_{42}^1 & a_{43}^1 & a_{44}^1
\end{bmatrix}
\]
The values of the above matrix elements can be calculated considering the quantitative values of each alternative for “Price” \((w_{1i}, i = 1, 2, 3, 4)\). The parametric calculations were explained in a previous section.

AHP gives more value to those alternatives with higher numbers. This means that the maximum number for a criterion has the highest value, so when minimum value of one criterion is ideal, all the quantitative values of that criterion should be inverted. In this way, the minimum numbers convert to maximum, having the highest value in AHP. In this example, two criteria “Price” and “Finance Rate” are ideal when their values are the minimum. Table A4.14 shows how the quantitative values of “Price,” which has minimum ideal value, should be converted before calculating the pairwise comparison matrix.

Table A4.14. Price Criterion with the Minimum Ideal Value

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Criterion</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ford Focus - 4dr Sdn SE</td>
<td>Price ($)</td>
<td>(w_{11} = \frac{1}{18,615})</td>
</tr>
<tr>
<td>Toyota Corolla - 4dr Sdn CVT S Plus SE</td>
<td>(w_{12} = \frac{1}{19,700})</td>
<td></td>
</tr>
<tr>
<td>Honda Civic - Sdn 4dr CVT LX</td>
<td>(w_{13} = \frac{1}{19,190})</td>
<td></td>
</tr>
<tr>
<td>Hyundai Elantra - 4dr Sdn Auto SE</td>
<td>(w_{14} = \frac{1}{18,200})</td>
<td></td>
</tr>
</tbody>
</table>

\[
A^1 = \begin{bmatrix}
a_{11}^1 &= w_{11} \quad \frac{1}{18,615} \\
a_{12}^1 &= w_{12} \quad \frac{1}{19,700} \\
a_{13}^1 &= w_{13} \quad \frac{1}{19,190} \\
a_{14}^1 &= w_{14} \quad \frac{1}{18,200} \\
a_{21}^1 &= \frac{1}{18,615} \quad w_{11} \\
a_{22}^1 &= \frac{1}{19,700} \quad w_{12} \\
a_{23}^1 &= \frac{1}{19,190} \quad w_{13} \\
a_{24}^1 &= \frac{1}{18,200} \quad w_{14} \\
a_{31}^1 &= \frac{1}{18,615} \quad \frac{1}{19,700} \\
a_{32}^1 &= \frac{1}{19,700} \quad \frac{1}{19,190} \\
a_{33}^1 &= \frac{1}{19,190} \quad \frac{1}{18,200} \\
a_{34}^1 &= \frac{1}{18,200} \quad \frac{1}{18,200} \\
a_{41}^1 &= \frac{1}{18,615} \quad \frac{1}{19,700} \\
a_{42}^1 &= \frac{1}{19,700} \quad \frac{1}{19,190} \\
a_{43}^1 &= \frac{1}{19,190} \quad \frac{1}{18,200} \\
a_{44}^1 &= \frac{1}{18,200} \quad \frac{1}{18,200} \\ 
\end{bmatrix}
\]
As mentioned above, the lower the “Finance Rate,” the better that alternative. To have higher values for those alternatives with low “Finance Rate,” the quantitative numbers should be inverted as shown in Table A4.15.

Table A4.15. Finance Rate Criterion with the Minimum Ideal Value

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Criterion</th>
<th>6</th>
<th>Finance Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1        Ford Focus - 4dr Sdn SE</td>
<td></td>
<td></td>
<td>$w_{61} = \frac{1}{2.90}$</td>
</tr>
<tr>
<td>2        Toyota Corolla - 4dr Sdn CVT S Plus SE</td>
<td></td>
<td></td>
<td>$w_{62} = \frac{1}{3.86}$</td>
</tr>
<tr>
<td>3        Honda Civic - Sdn 4dr CVT LX</td>
<td></td>
<td></td>
<td>$w_{63} = \frac{1}{1.90}$</td>
</tr>
<tr>
<td>4        Hyundai Elantra - 4dr Sdn Auto SE</td>
<td></td>
<td></td>
<td>$w_{64} = \frac{1}{3.90}$</td>
</tr>
</tbody>
</table>

The comparison matrix $A^6$ for the second criteria, fuel consumption, is:

$$A^6 = \begin{bmatrix}
\frac{w_{61}}{w_{61}} & \frac{w_{61}}{w_{62}} & \frac{w_{61}}{w_{63}} & \frac{w_{61}}{w_{64}} \\
\frac{w_{62}}{w_{61}} & \frac{w_{62}}{w_{62}} & \frac{w_{62}}{w_{63}} & \frac{w_{62}}{w_{64}} \\
\frac{w_{63}}{w_{61}} & \frac{w_{63}}{w_{62}} & \frac{w_{63}}{w_{63}} & \frac{w_{63}}{w_{64}} \\
\frac{w_{64}}{w_{61}} & \frac{w_{64}}{w_{62}} & \frac{w_{64}}{w_{63}} & \frac{w_{64}}{w_{64}} 
\end{bmatrix}$$
\[ A^6 = \begin{bmatrix} 1.0000 & 1.3310 & 0.6552 & 1.3448 \\ 0.7513 & 1.0000 & 0.4922 & 1.0104 \\ 1.5263 & 2.0316 & 1.0000 & 2.0526 \\ 0.7436 & 0.9897 & 0.4872 & 1.0000 \end{bmatrix} \]

In the same way, the comparison matrix for other criteria can be calculated. Other criteria except the “Finance Rate,” are intended to have high values; therefore, it is not required to include the inverse values in calculating the comparison matrix. High values for power, guarantee period, and trunk volume are more desirable.

\[ A^2 = \begin{bmatrix} 1.0000 & 0.9310 & 0.9000 & 0.9643 \\ 1.0741 & 1.0000 & 0.9667 & 1.0357 \\ 1.1111 & 1.0345 & 1.0000 & 1.0714 \\ 1.0370 & 0.9655 & 0.9333 & 1.0000 \end{bmatrix} \quad A^3 = \begin{bmatrix} 1.0000 & 1.2121 & 1.1189 & 1.0343 \\ 0.8250 & 1.0000 & 0.9231 & 0.9103 \\ 0.8938 & 1.0833 & 1.0000 & 0.9862 \\ 0.9063 & 1.0985 & 1.0140 & 1.0000 \end{bmatrix} \]

\[ A^4 = \begin{bmatrix} 1.0000 & 1.0000 & 1.0000 & 0.6000 \\ 1.0000 & 1.0000 & 1.0000 & 0.6000 \\ 1.0000 & 1.0000 & 1.0000 & 0.6000 \\ 1.6667 & 1.6667 & 1.6667 & 1.0000 \end{bmatrix} \quad A^5 = \begin{bmatrix} 1.0000 & 1.0154 & 1.0560 & 1.8919 \\ 0.9848 & 1.0000 & 1.0400 & 0.8784 \\ 0.9470 & 0.9615 & 1.0000 & 0.8446 \\ 1.1212 & 1.1385 & 1.1840 & 1.0000 \end{bmatrix} \]

When the pairwise comparison matrix for each criterion is calculated, then the priority matrix can be formed including all the criteria.

\[ PV^1 = \begin{bmatrix} 0.2540 \\ 0.2400 \\ 0.2463 \\ 0.2597 \end{bmatrix} \quad PV^2 = \begin{bmatrix} 0.2368 \\ 0.2544 \\ 0.2632 \\ 0.2456 \end{bmatrix} \quad PV^3 = \begin{bmatrix} 0.2759 \\ 0.2276 \\ 0.2466 \\ 0.2500 \end{bmatrix} \]

\[ PV^4 = \begin{bmatrix} 0.2143 \\ 0.2143 \\ 0.2143 \\ 0.3571 \end{bmatrix} \quad PV^5 = \begin{bmatrix} 0.2467 \\ 0.2430 \\ 0.2336 \\ 0.2766 \end{bmatrix} \quad PV^6 = \begin{bmatrix} 0.2487 \\ 0.1868 \\ 0.3796 \\ 0.1849 \end{bmatrix} \]
Applying two criteria with minimum ideal values have the maximum priority value in PV. The Hyundai has the lowest price, and the column one of PV, which is related to “Price,” has the maximum priority value for the fourth item related to Hyundai. The same description is true for “Finance Rate,” Honda has the lowest finance rate, and the last column of the PV related to finance rate has the maximum value for Honda. The values of priority vector for other criteria are shown to be correct by comparing the values of criteria in Table 2.4 and their values on the priority vector.

The priority of alternatives can be calculated by multiplying PV and PV_C:

\[
P * PV_C = \begin{bmatrix}
0.2503 \\
0.2337 \\
0.2630 \\
0.2530
\end{bmatrix}
\]

It means that the ranks of four selected cars and their values are:

1. Honda 0.2630
2. Hyundai 0.2530
3. Ford 0.2503
4. Toyota 0.2337
Appendix 5: A Code in Matlab for AHP

The following code is comprised of seven parts that are shown below. There is an explanation at the beginning of each part to illustrate the purpose of that part of the code because different inputs or outputs should be entered or calculated in each part of the code. This code can be copied in a Matlab *.mat file and be run. Different parameters in the code are explained below:

\( k \): Number of Criteria \((k = 1 .. m)\)

\( n \): Number of Alternatives

\( m \): Number of Criteria

\( A \): Matrix of Criteria of Different Alternatives

\( C \): Pairwise Comparison Matrix of Criteria

\( \text{LMc} \): Lambda Maximum of \( C \)

\( \text{RI} \): Random Consistency Index

\( \text{Clc} \): Consistency Index of \( C \)

\( \text{CRC} \): Consistency Ratio of \( C \)

\( \text{PVc} \): Priority Vector of \( C \)

\( \text{IC} \): Ideal Values of Criteria (‘H’ or ‘L’)

\( \text{Cl} \): Consistency Index of One Criterion

\( \text{CR} \): Consistency Ratio of One Criterion

\( \text{PVa} \): Priority Vector of One Criterion

\( \text{PV} \): Priority Vector Matrix of all Criteria
The following code is customized for ranking projects within a portfolio. It can be used for all other purposes if “project(s)” are substituted with “alternative(s)”.

clear all
clc

%------Part 1--------

%% Enter the information of decision-making situation %%%
%% Enter data of matrix A including the value of criteria for each project %%%

n = input('Number of Projects(n)=  ');
m = input('Number of Criteria(m)=  ');
str=['"""Enter data of matrix A including the value of Projects for each criterion"""'];
disp(str)
for j = 1:m
    for i = 1:n
        str = ['(i,j) = (', num2str(i), ',', num2str(j), ')'];
        disp(str)
        A(i , j) = input('Enter the Value of Project i for Criteria j = ');
    end
end

%------Part 2--------

%% Enter data of matrix C including the pairwise comparison of criteria %%%

str=['"""Enter data of matrix C including the pairwise comparison of criteria"""'];
disp(str)
for j = 1:m
    for i = 1:m
        str = ['(i,j) = (', num2str(i), ',', num2str(j), ')'];
        disp(str)
        C(i , j) = input('Enter the Pairwise Comparison of criterion i to j = ');
    end
end

%------Part 3--------

%% Calculate the priority vector for criteria pairwise comparison matrix %%%
%% C & maximum eigenvalue and CIc and CRc %%%
for j=1:m
    CSC(j)=sum(C(:,j));
    for i=1:m
        SC(i,j)=C(i,j)/CSC(j);
    end
end
end
for j=1:m
    PVc(j,1)=mean(SC(j,:));
end
str=['PVc ';disp(str);
str=['PVc ';disp(str);
PVc
%%%% Calculate the maximum eigenvalue (LMc), CIc, and CRc of C %%%%
PVL=zeros(m,1);
for j=1:m
    PVL=PVc(j,1)*C(:,j)+PVL;
end
for j=1:m
    LV(j,1)=PVL(j,1)/PVc(j,1);
end
LMc=mean(LV);str=['LMc = ', num2str(LMc)];disp(str)
CIc=(LMc-m)/(m-1);str=['CIc = ', num2str(CIc)];disp(str)
if m <= 2
    RI=0;str=['RI=0 and CRc=CIc/RI cannot be calculated!'];disp(str)
elseif m==3
    RI=.52;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==4
    RI=.89;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==5
    RI=1.11;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==6
    RI=1.25;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==7
    RI=1.35;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==8
    RI=1.4;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==9
    RI=1.45;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==10
    RI=1.49;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==11
    RI=1.51;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==12
    RI=1.48;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==13
    RI=1.56;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==14
    RI=1.57;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m==15
    RI=1.59;CRc=CIc/RI;str=['CRc = ', num2str(CRc)];disp(str)
elseif m > 15
    str=['The number of projects is out of range!'];disp(str)
end
%%%% Part 4------------Part 4------------Part 4------------Part 4------------Part 4------------Part 4------------Part 4------------Part 4------------

%%% Define the ideal value for criteria (use capital L or H... %%%
%%% wrapped with prime sign 'H' or 'L') %%%
str=['""""""Enter data of matrix C including the pairwise comparison of criteria""""""'];
disp(str)
for k = 1:m
    str = ['k = ', num2str(k)];
disp(str)
IC(k) = input('Ideal criteria k is L=Low or H=High? ');
end
IC = IC';

%------Part 5--------Part 5--------Part 5--------Part 5--------Part 5------

%%% Calculate the values of pairwise comparison matrix for each criterion %%%
for k=1:m
    for i=1:n
        for j = 1:n
            if IC(k)== 'H'
                a(i,j,k)= A(i,k)/A(j,k);
            else
                a(i,j,k)= A(j,k)/A(i,k);
            end
        end
    end
end

%------Part 6--------Part 6--------Part 6--------Part 6--------Part 6------

%%% Calculate the priority vector for pairwise comparison of projects...
%%% for different criteria %%%
for k=1:m
    for j=1:n
        CSA(j)=sum(a(:,j,k));
        for i=1:n
            Sa(i,j)=a(i,j,k)/CSa(j);
        end
    end
    for j=1:n
        PVa(j,1)=mean(Sa(j,:));
    end
    str=[m = ', num2str(k)];disp(str);
    PV(1:n,k)=PVa;

%%% Calculate the maximum eigenvalue (LMa), CIa, and CRa of a %%%

PVLa=zeros(n,1);
for j=1:n
    PVLa=PVa(j,1)*a(:,j,k)+PVLa;
end
for j=1:n
    LVa(j,1)=PVLa(j,1)/PVa(j,1);
end
LMa=mean(LVa);str=['LMa = ', num2str(LMa)];disp(str)
CIa=(LMa-n)/(n-1);str=['CIa = ', num2str(CIa)];disp(str)
if n <= 2
    RI=0;str=['RI=0 and CRa=CIa/RI cannot be calculated!'];disp(str)
elseif n==3
    RI=.52;CRa=CIa/RI;str=['CRa = ', num2str(CRa)];disp(str)
elseif n==4
    RI=.89;CRa=CIa/RI;str=['CRa = ', num2str(CRa)];disp(str)
else n==5
    RI=.89;CRa=CIa/RI;str=['CRa = ', num2str(CRa)];disp(str)
The pairwise comparison matrix of criteria (C) can be created in two forms: 1) Criteria are compared two by two, and 2) the weight of each criterion is decided and then the pairwise comparison matrix created by dividing the weights two by two. In the second case the CR is always zero. The code in part two can be modified to enter the criteria’s weights to calculate C instead of entering the entities of the C. In fact, the following code is developed to create pairwise comparison matrix of criteria for case 2.
%%% Enter the weight of each criterion to calculate the pairwise comparison matrix of criteria (C) %%%$
str=[""""Enter the weight of each criterion in comparison to others""""!
];
disp(str)

% for i=1:m
    str = ['Criteria Number: ', num2str(i)];
disp(str)
    ww(i) = input('What is the Weight of this Criteria? ');
end
for i = 1:m
    for j = 1:m
        str = ['(i,j) = (', num2str(i),',',num2str(j),')'];
disp(str)
        C(i , j) = ww(i)/ww(j);
    end
end
C