VIPOR: A Visual Analytics Decision Support Tool for Capital Investment Planning

Mark Rempel
DRDC – Centre for Operational Research and Analysis

Chad Young
DRDC – Centre for Operational Research and Analysis
VIPOR: A Visual Analytics Decision Support Tool for Capital Investment Planning

Mark Rempel
DRDC – Centre for Operational Research and Analysis

Chad Young
DRDC – Centre for Operational Research and Analysis

Defence Research and Development Canada
Scientific Report
DRDC-RDDC-2017-R129
November 2017
Abstract

Investment planning within a large public sector enterprise is often a complex process that requires considering hundreds of potential projects and millions of taxpayer dollars. The nature of this problem demands a portfolio optimization approach to generate a high quality investment plan. However, an optimization model alone is insufficient to support management decisions. Decision-makers need the ability to understand the portfolios generated by an optimization model and the underlying trade-offs that these portfolios contain. This article introduces a visual analytics decision support software called VIPOR which is an acronym for Visual Investment Planning Optimization & Revision (VIPOR). This software was developed to support the formulation of investment portfolios within the Department of National Defence and Canadian Armed Forces. It integrates a portfolio optimization model and several interactive information visualizations. Together, these allow for the construction, characterization, and adjustment of an investment portfolio in accordance with decision-maker preferences and practical constraints. In this report we: (1) characterize some of the necessary tasks to facilitate investment planning within a large organization that is making a shift toward a portfolio approach; (2) provide an overview of VIPOR and a description of how it can be used to build alternative portfolios; and (3) outline observations about the utility of this decision support system during the two years since its development.

Significance for defence and security

The significance of this work is that it provides the Department of National Defence and Canadian Armed Forces a decision support system, built on a rigorous, repeatable, and transparent process, to characterize, adjust, and compare candidate defence investment portfolios. This decision support system, known as VIPOR, lays a solid foundation for the implementation of continuous improvements to the way that Defence selects capital investment projects in accordance with budget limitations.
Résumé

La planification des investissements au sein d’une grande entité publique s’avère bien souvent complexe, car elle exige l’examen de centaines de projets potentiels et la gestion de millions de dollars provenant des contribuables. C’est pourquoi il convient d’adopter une stratégie d’optimisation des portefeuilles pour établir un plan d’investissement solide. Toutefois, les décisions de gestion ne peuvent pas reposer uniquement sur un modèle d’optimisation. Les décideurs doivent être en mesure de comprendre les portefeuilles issus de ce modèle et les compromis qu’ils impliquent. Le présent document a pour but de présenter un logiciel d’aide à la prise de décisions fondé sur une analyse visuelle, l’outil Visual Investment Planning Optimization & Revision (optimisation et révision du plan d’investissement par analyse visuelle – VIPOR), qui a été mis au point pour appuyer le ministère de la Défense nationale et les Forces armées canadiennes dans la composition des portefeuilles d’investissement. Le logiciel comprend un modèle d’optimisation des portefeuilles et plusieurs représentations visuelles interactives des données. Combinés, ces deux volets permettent de constituer, de définir et de modifier les portefeuilles d’investissement selon les préférences des décideurs et les contraintes pratiques. Le présent rapport vise à: 1) énoncer certaines des tâches à accomplir pour faciliter la planification des investissements au sein d’une grande organisation qui souhaite adopter une approche par portefeuilles ; 2) donner un aperçu du logiciel VIPOR et décrire comment celui-ci peut être utilisé pour établir d’autres options de portefeuilles ; 3) formuler des observations quant à l’utilité de cet outil d’aide à la prise de décisions depuis sa création il y a deux ans.

Importance pour la défense et la sécurité

Ces travaux sont importants du fait qu’ils offrent au ministère de la Défense nationale et aux Forces armées canadiennes un outil d’aide à la prise de décisions qui repose sur un processus rigoureux, reproductible et transparent permettant de définir, de modifier et de comparer les éventuels portefeuilles d’investissement dans la défense. Ce logiciel d’aide à la prise de décisions, connu sous l’acronyme VIPOR, jette des bases solides pour l’amélioration continue de la façon dont le ministère de la Défense choisit ses projets d’immobilisations en fonction des contraintes budgétaires.
Table of contents

Abstract ......................................................... i  
Significance for defence and security ........................ i  
Résumé .......................................................... ii  
Importance pour la défense et la sécurité .............. ii  
Table of contents .............................................. iii  
List of figures ................................................ iv  
List of tables .................................................. v  
1 Introduction ................................................... 1  
2 The context and impetus for VIPOR .................... 3  
3 The components of project portfolio development ..... 6  
4 Related work ................................................... 8  
5 The portfolio construction model ....................... 10  
6 Portfolio characterization & adjustment .............. 15  
7 The visual elements of VIPOR ............................ 22  
8 Example work flow ......................................... 33  
9 Implementation ............................................... 37  
10 Evaluation ..................................................... 38  
11 Future considerations ..................................... 41  
12 Summary ....................................................... 43  
References ....................................................... 45  
Acronyms ......................................................... 50
## List of figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Pictogram of the portfolio approach.</td>
<td>4</td>
</tr>
<tr>
<td>Figure 2</td>
<td>An example of a sequential approach for developing an investment plan.</td>
<td>4</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Project portfolio development process.</td>
<td>7</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Mapping of portfolio characterization and adjustment activities to high-level subtasks.</td>
<td>16</td>
</tr>
<tr>
<td>Figure 5</td>
<td>VIPOR’s nominal work flow.</td>
<td>17</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Description of high-level subtasks using the Brehmer and Munzner task typology.</td>
<td>18</td>
</tr>
<tr>
<td>Figure 7</td>
<td>VIPOR’s main control interface.</td>
<td>22</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Juxtaposed bubble cluster and treemap plots.</td>
<td>24</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Bullet charts.</td>
<td>27</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Bubble scatter plot and parallel coordinates.</td>
<td>28</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Criteria weight and project sensitivity triangle.</td>
<td>30</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Heatmap and scatter plot.</td>
<td>32</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Example of VIPOR work flow.</td>
<td>34</td>
</tr>
</tbody>
</table>
List of tables

Table 1: Examples of how decision support systems incorporate decision-maker insight. ................................. 9
Table 2: Multi-level abstract task typology. ........................................................................................................... 21
Table 3: Mapping tasks to visualizations. ............................................................................................................. 23
1 Introduction

Investment planning is a critical activity for an enterprise because it has lasting impact on its strategic direction, long-term sustainability, and overall success. The processes that enable the production of investment plans have many facets [1], including the breadth of investments considered and the methods used to select which investments to pursue. Organizations that take a holistic view of their potential investments and use a portfolio approach to make investment decisions increase their odds of achieving their strategic goals [2].

Many public sector enterprises have traditionally based their investment planning processes on the construction of a ranked list of candidate investments [3, 4, 5]. With this approach, cost estimates for candidate investment initiatives, hereafter referred to as projects, are determined. Projects are then ranked in order of priority and a financial cut-line, below which projects will not be funded, is used to identify the subset of projects that are selected for investment. Although the concept is simple, the ranked list approach can be challenging to implement when the portfolio must conform to many real-world constraints that have temporal aspects. For example, the ranked list approach treats financial and other resource limitations in terms of a single aggregate quantities. In actual fact, capital projects typically require funds across many years and the available budget to finance these projects changes from year to year.

Challenges with implementing the ranked list approach become even more acute when it is executed as a series of sequential steps performed by separate organizations internal to the enterprise—where evaluations of project importance, financial requirements, and organizational capacity to deliver projects, are conducted independently without a consistent view of the entire portfolio. Some challenges can be partially alleviated by partitioning projects into categories (e.g., equipment, infrastructure, informatics) and focusing on each category in isolation; however, this approach generates multiple investment plans that must then be merged together, which is a non-trivial task if the objective is to maximize the benefits across the whole portfolio.

In the past the Canadian Department of National Defence and the Canadian Armed Forces, hereafter referred to as Defence, have based their investment planning processes on a ranked list approach. However, a transition towards a portfolio-based approach has recently begun. This approach aims to enhance the method by which portfolios of projects are selected in accordance with strategic preferences and practical constraints [6]. To support this transition, we developed a decision support system for the visual optimization and revision of investment project portfolios called VIPOR.

From a user’s perspective VIPOR consists of two components: (1) a mathematical optimization model; and (2) a graphical interface containing a set of interactive information visualizations. These two components have been designed to be used in an iterative fashion. The former aims to construct a feasible project portfolio. The latter allows a decision-
maker to characterize candidate projects, understand alternate portfolios, and make manual
adjustments to a portfolio’s composition and its construction constraints.

In this report we present the first version of VIPOR. We begin by briefly delving into the
context and impetus for developing VIPOR. We then outline the project portfolio devel-
oped process that the first version of VIPOR was meant to facilitate. Related work in
the area of visual analytics and optimization, upon which we based our initial design ef-
forts, is then introduced. This is followed by an overview of the key ideas that underpin the
mathematical optimization model employed by VIPOR to create viable portfolios. Next,
we characterize some of the tasks required to enable the portfolio approach. We focus on
domain-specific investment planning tasks and the visualization tasks that are necessary
when an organization is transitioning towards a portfolio approach. We then describe the
visual elements of VIPOR and provide an example of how it is used. Finally, we outline
VIPOR’s implementation and present observations about user experience and potential ar-
eas for future work.

The main contributions of this report are as follows.

• A overview of several domain-specific tasks and the visualization tasks that a decision
support system should support in order to enable a large organization that is beginning a
transition toward a holistic approach to project selection and portfolio management.

• A visual analytics decision support system that integrates several interactive information
visualizations together with a mathematical optimization model that allows a user to
construct, characterize, and adjust a project portfolio.

• Observations about the utility of this decision support system for enabling investment
planning in a large public sector enterprise.

While our specific work efforts have focused on supporting the development of a long-term
investment plan for Defence, the techniques described herein could be applied within other
organizations engaging in long-term capital investment planning [7].
2 The context and impetus for VIPOR

VIPOR was developed to provide the analytical engine behind a new process called the Capital Investment Program Plan Review (CIPPR). This process is coordinated and overseen by the Chief of Force Development (CFD). CIPPR was formally initiated in 2014 through a directive from the Vice Chief of Defence Staff (VCDS) and the Associate Deputy Minister of Finance (ADM Fin) with the following aims.

1. Undertake a rationalization of all investments in the pre-identification, identification and options analysis stages in the project life-cycle that have an acquisition cost of greater than $5 million.

2. Produce a consolidated balanced portfolio of projects that will deliver critical, viable, and affordable capabilities and represent the best value for money.

3. Institutionalize a process that will be transparent, repeatable, rigorous and coherent against which all present and future investment will be assessed.

The directive tasked those Defence organizations that routinely participate in the development and/or execution of capital projects to collect the relevant project data and aid in assessment of all projects not yet within the definition phase of their life-cycle. These efforts were guided and coordinated by a CIPPR working group led by the Director General of Capability and Structure Integration (DGCSI), a subordinate of CFD.

The CIPPR working group was established in December 2013. As operational research analysts in support of the CIPPR working group, we (the authors) were involved in formulation discussions which led to the CIPPR directive. Subsequently we were also asked to: (1) provide scientific support toward the development of a traceable and sustainable approach by which to create project portfolios and make future investment decisions, and (2) develop analytical methods and associated toolsets to support the fulfilment of CIPPR aims.

Rather than tackle the three CIPPR aims in sequence, we proposed and then participated in the creation of a multi-pronged plan with several different elements. The first element of the plan was to develop and socialize a portfolio approach and an associated analysis process. A pictogram which illustrates the main components of the portfolio approach is presented in Figure 1. It requires the collection of project related data, the development of one or more portfolio options, decision processes by which to select a preferred option, and the development and execution of an investment plan by which to realize the selected portfolio.

The portfolio approach aims to address issues concerning preference, criticality, viability, affordability and coherence all at once, while simultaneously striving to achieve simplified governance requirements, improved understanding or portfolio related issues, and more timely decisions. For purposes of comparison, an alternate approach based on a series of
sequential decisions is illustrated in Figure 2. In it determinations about preference, criticality, viability, affordability and coherence are undertaken by different organizations within a pseudo-sequential process that is time consuming to govern, relatively inflexible to changing conditions/assessments, lacks a holistic view, and makes it difficult to show that best value for money is being achieved.

**Figure 1: Pictogram of the portfolio approach.**

![Figure 1: Pictogram of the portfolio approach.](image)

**Figure 2: An example of an sequential approach for developing an investment plan.**

After settling on the portfolio approach, other elements of the plan included [6]:

1. the development of an enhanced toolset for the collection and storage of project data;
2. the creation of a value model for assessing the relative merits of individual projects;
3. the formulation of an optimization model to facilitate the construction of project portfolios;
4. the development of interactive information visualizations that enable iterative modification of a project portfolio; and
5. the development and institutionalization of a portfolio definition process and related governance structures.

4 DRDC-RDDC-2017-R129
The focus of this report is items three and four, i.e., the optimization model and the interactive information visualizations. The result of addressing these two elements led to creation of VIPOR. The collection of project data, the value model, and the processes and governance structures developed for CIPPR are outside the scope of this report.

The first prototype version of VIPOR was developed by the authors between January 2014 and October 2014 in order to support the initial execution of CIPPR process between November 2014 and March 2015. Subsequently, several cycles of the CIPPR process have been undertaken. In 2016 outputs CIPPR outputs were considered during the Government of Canada’s review of Defence Policy, which in turn led to Canada’s latest white paper on Defence [8].

Since its inauguration, each time the CIPPR process has been improved each time it has been undertaken, however throughout its evolution VIPOR has remained a critical enabler. As mentioned in section 11, new efforts to make greater improvements to VIPOR are now being formulated. This report focuses on the extant version of VIPOR at the end of 2016.
3 The components of project portfolio development

At the outset of VIPOR’s development, its design requirements, including the required data, the high-level domain-specific tasks and the lower level tasks needed to support Defence’s implementation of a portfolio-based investment planning process, were unclear. To specify these, the design team synthesized relevant literature in the areas of project portfolio management and defence investment planning. We also held discussions with a cross-functional investment planning working group and several executive decision-makers. Although there are many steps in the recognized project portfolio management process, we determined from these efforts that VIPOR should enable the integration of a reduced subset of high-level domain-specific tasks as follows.

- **Portfolio Construction**: Construct a project portfolio that respects resource constraints, organizational capacity constraints, and project dependencies over future time horizons. This construction must also explicitly account for the views of different Defence stakeholders as prescribed by criteria within an underlying value model that computes each project’s merit toward the mission, mandate, and sustainability of the enterprise.

- **Portfolio Characterization**: Characterize a portfolio by its aggregate attributes, e.g., compositional balance and utilization of resources. In addition, enable the examination of differences between alternative portfolios.

- **Portfolio Adjustment**: Facilitate the manual adjustment of a portfolio’s composition in accordance with decision-maker preferences, either directly through the addition and/or removal of projects, or indirectly by altering portfolio construction constraints or modifying parameters within the aforementioned value model.

To communicate these high-level domain-specific tasks, the VIPOR design team constructed the process model depicted in Figure 3. It combines concepts derived from Archer & Ghasemzadeh [9], who describe an integrated framework for project portfolio selection, and Keim et al. [10] who describe a sense-making loop for visual analytics.

The process model in Figure 3 illustrates that project data, organizational resource constraints, parameter settings within the value model, and the computed merit ascribed to individual projects are all fed into a mathematical optimization model which subsequently constructs a viable project portfolio. A variety of visualizations then serve to enhance the user’s knowledge about the portfolio’s composition and its characteristics.

Underlying Figure 3 is a database which organizes and saves the critical information and outputs from each step so that the entire process remains traceable. With this database the process of portfolio construction, portfolio characterization, enhanced user knowledge, and portfolio adjustment can ensue in an iterative fashion until a portfolio is created that best meets user preferences.
Figure 3: An overview of the project portfolio development process. The components that exist within VIPOR are shown in blue.
4 Related work

Optimization techniques have been used to construct investment portfolios in the context of investment planning within defence organizations since the 1950s [11]. However, as pointed out in a recent survey by Burk [12], the application of mathematical optimization is not as widespread as one may expect. A key reason is that it is typically used to prescribe solutions without directly engaging a decision-maker, or allowing a decision-maker to impart their judgement, experience, and insight to help steer the solution process [13]. In other words, it has not been the tradition to use optimization models within a process that explicitly includes interaction and feedback as depicted in Figure 3.

However, outside the military domain, attempts have been made to design and build decision support systems that make explicit use of decision-maker insight when planning a portfolio (e.g., personal investment planning [14, 15, 16] and corporate investment planning [17, 18, 19, 20, 21]). Some examples from the open literature, including brief descriptions of the optimization and visualization techniques employed within them, are listed in Table 1.

As demonstrated in Table 1, these systems typically employ: (1) an optimization technique to construct an initial portfolio; (2) simple visualizations such as pie charts, bar graphs, and time-series graphs to characterize the portfolio; and (3) manual methods (e.g., updating data tables) to adjust the portfolio based on user preferences.

Beyond the examples in Table 1, there have also been attempts to use increasingly sophisticated visualizations for characterizing portfolios and to examine differences between them. One of the most popular visualizations is the bubble plot [22]. Bubble plots are typically used to characterize a portfolio across two or three dimensions. Treemaps have also been used. For example, Jungmeister & Turo [23] use a treemap to determine buy vs. sell conditions, performance, and market activity of stock portfolios. Cable et al. [24] use a treemap to visualize project portfolios and explore project performance, and Csallner et al. [25] use treemaps to compare the overlap between mutual fund holdings. In addition, self-organizing maps [26, 27], heatmaps [28, 29], and parallel coordinates plots [29] have also been used to characterize and compare portfolios.

A main observation from this literature is that there are few instances that: (1) employ visualizations to compare portfolios during an iterative and interactive portfolio development process; and (2) integrate sophisticated visualizations with the use of mathematical optimization to enable a decision-maker to enhance their knowledge and impart their insight to adjust a portfolio's content while at the same time also ensuring conformance to a set of selectable practical constraints. These two aspects were deemed necessary for VIPOR to be successful. The first helps decision-makers understand the impact of proposed alterations and assess what-if scenarios. The second helps engage and retain decision-maker interest and efficacy of their decisions. Of course these two aspects are not independent.
Table 1: Examples of techniques used in decision support systems that aim to incorporate decision-maker insight to construct, characterize, and adjust a project portfolio.

<table>
<thead>
<tr>
<th>Decision Support System</th>
<th>Portfolio Construction</th>
<th>Portfolio Characterization</th>
<th>Portfolio Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal-Asset Allocation Tool [14]</td>
<td>Multiple portfolios are created, using a scenario optimization model, and stored in a database. The database is searched for the portfolio that most closely resembles the user’s preferences.</td>
<td>Bar charts, pie charts, and tables.</td>
<td>Editable tables allow a user to add or remove projects from a portfolio according to user preferences. The portfolio can not be re-optimized taking into account these preferences.</td>
</tr>
<tr>
<td>FinVis [15]</td>
<td>A portfolio is constructed manually by a user.</td>
<td>Time-series graphs and tables.</td>
<td>Editable tables allow a user to add, remove, and modify investments from the portfolio.</td>
</tr>
<tr>
<td>Portfolio-Compare [16]</td>
<td>Portfolios are constructed manually by a user.</td>
<td>Tornado diagrams, scatter plots, and tables.</td>
<td>Slider bars, which adjust the percentage invested in a given fund, are used to create portfolios. Portfolios may also be deleted.</td>
</tr>
<tr>
<td>Project Analysis and Selection System [18]</td>
<td>A portfolio is constructed using an integer linear programming model.</td>
<td>Scatter plots and Gnatt charts.</td>
<td>A portfolio can be adjusted, however the article does not clearly indicate how this is accomplished.</td>
</tr>
<tr>
<td>Capital Investment Planning Aid [19]</td>
<td>A portfolio is constructed using an integer linear programming model and a customized local-search heuristic solver.</td>
<td>Time-series graphs and tables.</td>
<td>The report indicates a portfolio can be adjusted, however it is not clear how this is accomplished.</td>
</tr>
<tr>
<td>Dickinson et al. [17]</td>
<td>A portfolio is constructed using a nonlinear integer programming model.</td>
<td>Scatter plot, bar charts, and tables.</td>
<td>A project can be added or removed from a portfolio. However, the article does not indicate if the portfolio can be re-optimized when taking into account these constraints.</td>
</tr>
<tr>
<td>Stummer and Heidenberger [20]</td>
<td>Pareto optimal portfolios are constructed using a multi-objective integer linear programming model.</td>
<td>Bar charts.</td>
<td>Rather than adjustment, the set of Pareto optimal portfolios are iteratively searched by setting upper/lower bounds on objectives until an acceptable portfolio is found.</td>
</tr>
<tr>
<td>AES Project Manager [21]</td>
<td>A portfolio is constructed using a metaheuristic.</td>
<td>Bar charts, time-series graphs, and tables.</td>
<td>Project parameters can be adjusted. The portfolio can be re-optimized taking into account these modifications.</td>
</tr>
</tbody>
</table>
5 The portfolio construction model

To understand how visualization can be used connect human judgement with mathematical optimization, it is important to have a basic understanding of the portfolio construction model. Specifically, the construction of a portfolio from a set of candidate projects is couched as a type of combinatorial optimization problem, i.e., a 0–1 knapsack problem [30]. To illustrate, suppose there is a set of items that are to be put inside of a knapsack that has a limited volume, and that, in aggregate, the set of all items will exceed the volume limit. Also suppose that a quantified estimate of intrinsic value to the person who is filling the knapsack is assigned to each item. The objective when trying to solve the knapsack problem is to fill the knapsack with only those items that, in aggregate, provide the maximum intrinsic value to the knapsack’s owner while at the same time ensuring that the knapsack’s total volume constraint is not exceeded.

The basic 0–1 knapsack model can be extended. For example, the knapsack may also have a weight limitation and it may also have a specific shape or profile that will constrain how items are put into it. Additionally, there may be dependencies between the items (e.g., if one item is chosen then another item can not be chosen), and there may be multiple knapsacks to fill. When a problem includes several knapsacks and a series of constraints, it is described as a 0–1 multiple knapsack problem with multiple constraints. The portfolio construction problem within VIPOR is a problem of this type. Specifically, the objective is to select the set of projects to fill two knapsacks, each with a particular shape profile, so that the aggregate value accrued by the enterprise is maximized.

In this analogy the two knapsacks correspond to the two financial sources of funding for projects within Defence’s hybrid financial system [31]. The first knapsack corresponds to Defence’s accrual funding envelope, and the second knapsack corresponds to its cash-based funding envelope. With accrual-based funding, a capital asset’s cost is distributed over its useful life. With cash-based funding, costs are born up-front during the period of acquisition. Both knapsacks extend beyond a projected time horizon of 20 years and both limit the amount of funding that is available for projects in each fiscal year.

The fundamental aspects of VIPOR’s portfolio construction model are as follows:

(a) **Projects are indivisible and project selection is binary**: Projects can not be subdivided; either a project is selected for inclusion in the portfolio or it is not. Additionally, duplicate copies of a project can not exist in the portfolio.

(b) **Projects can have multiple variants**: Multiple options to implement each project may exist. Some options may cost more and some may cost less. Correspondingly, project variants may have a different degrees of intrinsic value. Only a single variant of each project may be selected for inclusion in the portfolio.
(c) **Projects typically demand funding over several years:** For each project variant a profile of annual funding demand is forecasted and used to determine the viability of incorporating the project into the portfolio.

(d) **Projects may be funded from one of two sources of financial supply:** For each project variant two financial demand profiles can be identified—a cash-based profile and an accrual profile. However, only one of these funding sources can be used to fund the project.

(e) **The value of each project variant is determined based on three criteria:** The proxy used to represent the intrinsic value of each project variant to the enterprise includes three criteria: (1) alignment with National Policy, (2) alignment with institutional/capability needs, and (3) the relative importance placed on the project variant by the project’s sponsor. The overall value of a project variant is computed as a linear weighted sum of the project’s score against each of these criteria. The weight factors used within this sum are set by the decision-makers and add up to one.

(f) **Each project variant may begin anytime within a range of years:** Projects may be shifted in time to make the best use of resources. As such, each project variant can begin at any year within a predefined time-window. Time-windows are defined for each project. The computed value of a project is typically not dependent on the year in which the project begins.⁴

(g) **The value of a knapsack:** There are two knapsacks. One knapsack corresponds to the multi-year envelope of available accrual funding. The other corresponds to the multi-year envelope of available cash-based funding. The total value of each knapsack is computed by summing the values of the projects within it.

(h) **The value of the portfolio:** The value of the whole portfolio is computed as the sum of the values of the accrual knapsack and the cash-based knapsack. The set of projects that maximize the portfolio’s value is called the optimal portfolio.

(i) **The portfolio is constrained by the organization’s practical capacity to deliver projects:** The model accounts for the limited capacity of the three main organizations within Defence that deliver capital projects (i.e., the Materiel, Infrastructure, and Information Technology delivery organizations) by way of three separate fiscal proxies. These proxies set an upper limit on the amount of money that can be spent on projects delivered by each organization in every fiscal year.

(j) **All available fiscal resources do not have to be utilized:** It is not a requirement to fully consume the whole supply of cash-based and accrual funding. In fact, the model allows for under- and over-programming. The model can be adjusted so that in

---

⁴ At present VIPOR does not explicitly discount cash flows or project benefits to account for the time value of money.
each year the portfolio of projects will only utilize up to a specified percentage of the available funding in each of the cash-based and accrual budgets. In practical terms, leaving a certain amount of funding unallocated allows for the addition of projects that have yet to be named. It can also be used to pay for potential cost overruns.

(k) **Dependencies between projects can be explicitly accounted for:** The inclusion or exclusion of a certain project may preference the inclusion or exclusion of other projects. For example, a one-way project dependency implies that the inclusion of a particular project requires the inclusion of another project, but not vice-versa. A two-way dependency indicates that, for two dependent projects, both must either be included or excluded from the portfolio.

The portfolio construction model is implemented as an integer programming model which is formulated below.

- Equation 1 expresses the total value of a portfolio, which is the objective function to be maximized.
- Equation 2 is a financial constraint that ensures that the sum of the total demand for fiscal resources across all selected projects does not exceed the available budget in each year.
- Equation 3 ensures that at most one variant, funding source, and start year option is selected for each project.
- Equation 4 ensures that the capacity required to deliver the selected projects in each year does not exceed available organizational capacity to deliver projects in each fiscal year.
- Equation 5 ensures that project dependencies are respected.
- Equation 6 states that projects are indivisible and project selection is binary.

**Objective function:**

$$\max \sum_{(p,v,f,\delta) \in D} \left( \sum_{c \in C} w_c \cdot a_{p,v,c} \cdot s_{p,v,f,\delta} \right). \quad (1)$$
Constraints:

\[
\sum_{(p,v,f,\delta) \in D} (r_{p,v,\delta,f,y} \cdot s_{p,v,f,\delta}) \leq \omega_{f,y} \cdot b_{f,y}, \quad \forall f \in F, \quad y \in Y, \tag{2}
\]

\[
\sum_{(p,v,f,\delta) \in D} s_{p,v,f,\delta} \leq 1, \quad \forall p \in P, \tag{3}
\]

\[
\sum_{(p,v,f,\delta) \in D} (\alpha_{p,v,\delta,o,y} \cdot s_{p,v,f,\delta}) \leq k_{o,y}, \quad \forall o \in U, \quad \forall y \in Y, \tag{4}
\]

\[
\sum_{(i,v,f,\delta) \in D} s_{i,v,f,\delta} - \sum_{(j,v,f,\delta) \in D} s_{j,v,f,\delta} \geq 0, \quad \forall (i,j) \in I, \tag{5}
\]

\[s_{p,v,f,\delta} \text{ binary.} \tag{6}\]

The decision variables, sets and parameters in the equations above are defined as follows:

**Decision Variables**

\[s_{p,v,f,\delta} \quad 1, 0; 1 \text{ if project } p \text{ and its variant } v \text{ is selected to be funded by funding source } f \text{ starting in year } \delta, 0 \text{ otherwise.}\]

**Sets**

- \(p, P\) is the index and the set of projects;
- \(v, V_p\) is the index and set of variants for project \(p\);
- \(f, F\) is the index and set of funding sources;
- \(\delta, \Delta_p\) is a start year and the set of start years for project \(p\);
- \(c, C\) is the index and set of criteria;
- \(y, Y\) is the index and set of years;
- \((p, v, f, \delta), D\) is a quadruple of project, variant, funding type, and start year indices in the decision set \(D\);
- \(o, U, O\) is the index, the user selected set of organizations with capacity limitations regarding implementation of projects, and the complete set of organizations with capacity limitations (i.e., \(U \subseteq O\));
- \((i, j), I\) is the set of pairs of project interdependencies \((i, j), \text{ where } i, j \in P\);

**Parameters**

- \(w_c\) is the weight of criteria \(c\); all weights must be greater than 0 and the sum of the weights must be 1;

(continued on next page)
Parameters

- $a_{p,v,c}$ is the value of variant $v$ of project $p$ for criteria $c$;
- $r_{p,v,\delta,f,y}$ is the requested funding by variant $v$ of project $p$, when starting in year $\delta$, in funding source $f$ in year $y$;
- $\omega_{f,y}$ is the maximum percentage of the available funding in funding source $f$ in year $y$ that should be consumed;
- $b_{f,y}$ is the funding limit in funding source $f$ in year $y$;
- $\alpha_{p,v,\delta,o,y}$ is the capacity consumed by variant $v$ of project $p$, when starting in $\delta$, in organization $o$ in year $y$;
- $k_{o,y}$ is the capacity limit in organization $o$ in year $y$;

This integer programming model is solved using two algorithms: (1) a branch & bound algorithm [32] is used to determine the optimal portfolio; and (2) a simplex algorithm [33] is used to compute a solution to an approximation of the actual problem. In this approximation individual projects be can divided so that instead of choosing the whole project, only a portion of a project (e.g., 75%) can become part of the portfolio.

The solution obtained by the branch & bound algorithm is the solution that subsequently becomes the subject of portfolio characterization and adjustment within VIPOR. The solution computed using the simplex algorithm provides an upper bound on the total value of the optimal portfolio subject to the constraints. This upper bound provides a benchmark upon which to gauge the quality of the integer solution provided by the branch & bound algorithm when a limited time is available to solve the problem—in other words, if the branch & bound algorithm is afforded an unlimited amount of time to compute a portfolio, it will produce a solution whose total portfolio value is very close to the solution computed by the simplex algorithm. However, if a time limit is set (e.g., 15 seconds), as is required when the model is employed in-situ with a decision-maker, the branch & bound algorithm returns the best solution found within the time allowed. In this case it is useful to have an estimate of solution quality. Although enforcing a time limit may lower the quality of portfolio produced by the algorithm, it helps to ensure that a user can interact with the application in a timely manner.
6 Portfolio characterization & adjustment

In this section, we describe the underlying tasks of the portfolio characterization and adjustment components in Figure 3. These lower-level tasks were deduced via a three-step process that borrowed elements from thematic analysis [34]. First, we reviewed literature in the field of project portfolio management [2, 3, 9, 35, 36] and captured information from discussions with CIPPR working group about conducting investment planning activities. Next, we extracted phrases, relevant to portfolio characterization and adjustment, from this information and generated codes to represent groups of similar phrases. For example, from [3] we used the code ‘Trade-offs’ to characterize phrases like:

‘... make trade-offs among competing projects ...’, and

‘... points out weaknesses and risks in the portfolios and suggests potential trade-offs.’

Likewise, for the code ‘Compare new assets versus maintain’ we associated phrases like:

‘... identify capital assets and facilities that are ageing and that may require maintenance, upgrade, or replacement in the near term or in the future ...’, and

‘... ensure that the purchase of new assets and infrastructure will have the highest and most efficient returns to the taxpayer and to the government, and that existing assets will be adequately repaired and maintained ...’

In total, we generated 26 codes. Finally, based on similarities between the codes, we developed five common themes. The mapping between the 26 codes and the five themes is depicted in Figure 4. These themes became the underpinning subtasks of the portfolio characterization and portfolio adjustment components in Figure 3. The five subtasks are as follows: (1) characterize portfolio composition, (2) characterize resource utilization, characterize projects, adjust portfolio, and compare portfolios. Identifying these five high-level subtasks was an important step in our efforts to achieve greater clarity about what VIPOR would be required to enable.

Figure 5 depicts how these five high-level subtasks can be linked together to create a workflow that allows a decision-maker to characterize and adjust a portfolio. First an initial portfolio is created using the portfolio construction model. The next step is to characterize the portfolio in terms of its project composition and aggregate characteristics. Following this assessment, the next step is to characterize the resources available and those consumed by the portfolio, compare these resource profiles, and summarize periods of high and low resource usage. Once these periods have been determined, the decision-maker may then identify particular projects for scrutiny or understanding. At this point, the decision-maker can apply their judgement to accept the portfolio as is, or to make manual adjustments by,
say, forcing certain projects into the portfolio and removing other projects from the portfolio. The decision-maker may also choose to alter or deactivate certain constraints within the portfolio construction model. For example it may be desirable to adjust constraints that limit the organization’s capacity to deliver projects. The impacts of adjustments can be understood by comparing the newly constructed portfolio with previously constructed portfolios, and the entire process can be repeated in an iterative fashion until a portfolio is produced that meets decision-maker preferences.

Figure 4: Mapping of 26 codes (rectangles) related to portfolio characterization and adjustment and their relation to five high-level subtasks (circles): characterize portfolio composition; characterize resource utilization; characterize projects; adjust portfolio; and compare portfolio.
**Figure 5:** A nominal work flow that connects the five domain-specific high-level subtasks that are identified in Figure 4. These subtasks (yellow rectangles) underlie the portfolio characterization and portfolio adjustment components of Figure 3. The other subtasks (white rectangles) are associated with the portfolio construction and user interaction components of Figure 3.

Of course the work flow depicted in Figure 5 is not the only way the five subtasks can be linked together. For example, an alternative is to characterize individual projects, identify a subset of those that must be included in the portfolio, and then use the optimization model to construct the remaining part of the portfolio. However, while this and other approaches are valid, the work flow in Figure 5 was deemed to be the likely use-case—it is easier to start with a pre-constructed portfolio and then make alterations rather than to start from scratch.

Whereas the analysis of requirements leading to Figure 5 was useful for narrowing down the business tasks, subtasks and a nominal work flow, a systematic method by which to transition between these and the specific visualisation requirements for VIPOR was still needed. For this we turned a multi-level abstract visualization task typology recently developed by Brehmer & Munzner [37, 38, 39]. The result of using this typology is shown in Figure 6 where each of the five subtasks are broken down into more granular visualization tasks. We selected this multi-level typology, rather than other low-level [40, 41, 42] or high-level [43, 44, 45] approaches, because it is designed to provide a systematic way to bridge determinations about why a visualization task is to be performed and how these visualization tasks are actually accomplished. We also found that the typology’s visual notation became useful for purposes of communication among the design team. For purposes of brevity in this report we only illustrate our use of the typology’s why components, which are summarized in Table 2. In discussions that follow we describe the breakdown of the five tasks as shown in Figure 6 using fixed-width font to highlight vocabulary taken from Table 2.
### Figure 6: The five subtasks identified in Figure 5 described using the Brehmer and Munzner [37, 38, 39] abstract task typology. Yellow boxes indicate why a task is performed. Grey boxes provide general information about what the task’s inputs and outputs are. Note that the characterize resource utilization subtask requires the output of characterize portfolio composition subtask, and the characterize projects subtask requires input from both the characterize portfolio composition subtask and the characterize resource utilization, etc.
Characterize portfolio composition – Figure 6(a): An ability to characterize what is included and not included in a portfolio, and the associated impacts of these choices, is a fundamental part of creating a viable portfolio. With a portfolio that has already been constructed via the optimization model, a decision-maker may want to: discover the portfolio’s composition in terms of its compositional and aggregate characteristics; produce screen shots of annotated visualizations that explain these characteristics; and present the portfolio’s composition to support decision-making by executive boards.

In order to discover a portfolio’s composition, a user will: explore the portfolio’s content; identify projects; compare subsets of projects in terms of their attributes including organizational sponsor, delivery risk, etc.; and summarize the portfolio’s composition. Likewise, to present a portfolio a decision-maker will: lookup and identify specific projects, compare subsets of projects, and summarize the portfolio’s composition. The key difference between discovering and presenting a portfolio is how its contents are searched. When discovering a portfolio its contents are unknown a priori (i.e., explore), whereas when presenting a portfolio its contents are known beforehand (i.e., lookup).

Characterize resource utilization – Figure 6(b): The available supply of resources is a key limiter when constructing a portfolio. Therefore, in addition to characterizing a portfolio’s composition, there is typically a need to: discover a portfolio’s resource usage; produce annotated visualizations that explain this usage; and present this resource usage to support decision-making in executive boards. Discovering a portfolio’s resource usage requires a user to explore the consumption of different types of available resources and compare resource usage during different time periods to identify choke points and periods or resource slack. When presenting the portfolio’s resource consumption, a decision-maker will lookup periods of high and low resource usage and summarize the overall use of resources.

Characterize projects – Figure 6(c): Characterizing the attributes of individual projects allows a user to develop more detailed insight into a portfolio’s composition and its resource consumption. To discover a project, a user will first browse the portfolio’s composition and identify a project. Once a project is identified a user will first characterize it by discovering its various attributes, (e.g., project outcomes, delivery risks and cost profiles) and then producing an annotated project summary.

Adjust portfolio – Figure 6(d): Once a user has characterized the composition of a portfolio, identified periods of high and low resource usage, and investigated individual projects, it may become desirable to make manual adjustments to the portfolio. This can be done in two basic ways, by directly adjusting the contents of the portfolio, or by adjusting criteria weight factors within the value model.

To adjust the contents of the portfolio, a decision-maker will discover the portfolio’s composition, lookup projects that are candidates to be moved into or out of the portfolio,
and of those projects identify specifics ones that will be inserted or removed.

To adjust the criteria weighting parameters in the value model, a decision-maker will discover the relationship between the project value and the criteria’s weights, explore how alterations to the criteria weights can lead to the inclusion or exclusion of projects from the portfolio, and identify preferred weights for each criteria. Regardless of the type of adjustment, the user’s new preferences will be reflected in updates to the portfolio optimization model and then a new portfolio will be computed.

**Compare portfolios – Figure 6(e):** Once a new portfolio has been computed it is often of interest to compare this new portfolio with previous portfolios. For example, in cases where particular projects have been manually added or removed from a portfolio by a user, other projects might need to be dropped or added to the portfolio by the optimization algorithm in order to ensure that the resulting portfolio adheres to construction constraints. Comparing the before/after states of a portfolio which has been manually adjusted helps to facilitate analysis of the opportunity costs. In other words, by manually adding particular projects to the portfolio the opportunities associated with those projects that were displaced from the portfolio are lost. To discover differences and similarities between portfolios (e.g., opportunity costs), a user will explore the composition of each portfolio and compare the results of user-directed changes between consecutive iterations of the portfolio construction process.
**Table 2: Summary of the why lexicon from the Brehmer & Munzner [37, 38, 39] multi-level abstract task typology.**

<table>
<thead>
<tr>
<th>Level</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I</strong></td>
<td>The first level of the typology identifies common reasons for undertaking a visualization task – to <strong>consume</strong> existing or new information for purposes of <strong>presentation</strong>, <strong>discovery</strong> or <strong>enjoyment</strong>, or to <strong>produce</strong> new information through <strong>derivation</strong> or <strong>annotation</strong> of existing data elements, or by <strong>recording</strong> user interactions. Descriptions of these terms follow below.</td>
</tr>
<tr>
<td><strong>Present</strong></td>
<td>There is a need for succinct communication of information for purposes of telling a story with data and/or for guiding an audience through a series of cognitive operations (e.g., presentation for purposes of decision-making, planning, forecasting, instruction).</td>
</tr>
<tr>
<td><strong>Discover</strong></td>
<td>There is a need to generate and/or verify hypotheses that are often motivated by existing theory, models or the observation of unexpected phenomena (e.g., the discovery and analysis of new information).</td>
</tr>
<tr>
<td><strong>Enjoy</strong></td>
<td>There is a desire to inspire casual observation that stimulates curiosity and can motivate further exploration. Note: casual observation may be initiated by the novelty of a particular visualization.</td>
</tr>
<tr>
<td><strong>Derive</strong></td>
<td>There is a need compute new elements of persistent data based on the existing elements of a visualization.</td>
</tr>
<tr>
<td><strong>Annotate</strong></td>
<td>There is a need to add or attach new graphical artefacts, textual information or attributes to existing elements of a visualization.</td>
</tr>
<tr>
<td><strong>Record</strong></td>
<td>There is a need to save or capture visualization elements as persistent artefacts for subsequent use (e.g., recording the history of interactions with various visualizations in order to trace the origin of the existing state of a visualization, and to allow a user to revisit earlier states or parameter settings).</td>
</tr>
<tr>
<td><strong>II</strong></td>
<td>The second level of the typology highlights that fact that when there is a need to present, discover or enjoy a visualization, the user must <strong>search</strong> for elements of information (also called <strong>targets</strong> of interest) by executing certain activities. These activities are differentiated based on whether the user knows the identity and location of the target <strong>a priori</strong>.</td>
</tr>
<tr>
<td><strong>Lookup</strong></td>
<td>There is a need to uncover targets of interest where identity and location of these targets are known <strong>a priori</strong>.</td>
</tr>
<tr>
<td><strong>Locate</strong></td>
<td>There is a need to uncover targets that have a known identity but the location of these targets is unknown <strong>a priori</strong>.</td>
</tr>
<tr>
<td><strong>Browse</strong></td>
<td>There is a need to uncover targets with particular characteristics. The location of these targets can be narrowed down quickly but their identities are unknown <strong>a priori</strong>.</td>
</tr>
<tr>
<td><strong>Explore</strong></td>
<td>There is a need to uncover targets in cases where both the location and identity of these targets are unknown <strong>a priori</strong>.</td>
</tr>
<tr>
<td><strong>III</strong></td>
<td>The purpose of the third level of the typology is to further characterize the results obtained from the search activities in Level II. This is accomplished by <strong>identifying</strong> further reference or characteristic information about a target, <strong>comparing</strong> targets and/or <strong>summarizing</strong> across targets. The main distinction between identify, compare and summarize is the number of targets under consideration.</td>
</tr>
<tr>
<td><strong>Identify</strong></td>
<td>There is a need to obtain either identification or reference information about a target.</td>
</tr>
<tr>
<td><strong>Compare</strong></td>
<td>There is a need to characterize the similarities and dissimilarities between two or more targets.</td>
</tr>
<tr>
<td><strong>Summarize</strong></td>
<td>There is a need to extract the most salient aspects about an ensemble of targets (e.g., summary info, distribution information, statistics).</td>
</tr>
</tbody>
</table>
7 The visual elements of VIPOR

VIPOR is implemented as a web application. In this section we briefly introduce each of VIPOR’s main visual elements. In the next section we present an example to illustrate how a user might interact with these to construct, characterize, and adjust a portfolio as per the work flow presented in Figure 5.

The Control interface: The control interface shown in Figure 7 is the first web page presented to a new user. Across the top of this interface is a control ribbon with the following items: Utilities, Set Parameters, Run Algorithm, Assess Portfolio, Assess Projects and Assess Development. This interface provides functionality to: (a) select and load the set of project and portfolio related information that will be applicable to the user’s current session; (b) set values for the criteria’s weights that determine the value of each project; (c) select the constraints to which the portfolio of projects must conform; and (d) set configuration parameters that control the performance of the optimization algorithms.

![VIPOR's main control interface](image)

**Figure 7: VIPOR’s main control interface. Navigation through VIPOR is enabled by menus that are accessed through the control ribbon. The visual elements that can be accessed from each menu are indicated in Table 3.**

VIPOR’s user community consists of individuals from a variety of internal organizations, including finance and military capability development. Each user has unique expertise, interests, experience with software, and personality traits. Such characteristics have been shown to impact the ability of a user to comprehend visualizations [46] and perform visualization-related tasks [47, 48, 49]. Our approach to address these disparities was to design one or more visualizations to perform each of the high-level subtasks in Figure 5. Additionally, we chose not to create the ribbon menu items in direct accordance with the five subtasks. Instead, after user trials with initial VIPOR prototypes, the ribbon items, their order, and their underlying submenus were determined in a way to best facilitate the introduction and initial use of VIPOR by an untrained user. For purposes of illustration the mapping between ribbon menus and the subtasks is shown in Table 3. As their names sug-
gest, visualizations accessed through the *Assess Portfolio* menu primarily facilitate characterization of a portfolio’s composition and resource utilization; visualizations accessed through the *Assess Projects* menu focus on individual projects; and the *Assess Development* menu facilitates the comparison of portfolios between iterations. Portfolio adjustment can be accomplished through visualizations accessed from several menus.

**Table 3:** Mapping tasks to individual visualizations. A checkmark indicates that a task may be performed by a given visualization.

<table>
<thead>
<tr>
<th>Ribbon Menu</th>
<th>Visualization</th>
<th>Characterize portfolio composition</th>
<th>Characterize resource utilization</th>
<th>Characterize projects</th>
<th>Adjust portfolio</th>
<th>Compare portfolios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assess Portfolio</strong></td>
<td>Juxtaposed bubble cluster plot</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Juxtaposed treemap plot</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Sets of bullet charts along a timeline</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Configurable bubble-scatter plot</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Assess Projects</strong></td>
<td>Parallel coordinate plot of project details</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Model dialogue of project details</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Project inclusion sensitivity triangle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>Assess Development</strong></td>
<td>Heatmap of portfolio composition by iteration</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Scatter plot of portfolio value by iteration</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

**Juxtaposed bubble-cluster plot—Figure 8(a):** This plot illustrates both the composition of the portfolio and the amalgam of projects that are under consideration but have not been included in the portfolio. Each bubble represents a project and the size and colour of each project is configurable to encode project attributes according to user preference. Normally bubble size encodes either project cost or project value; bubble colour encodes the organization that is sponsoring the project; and hue is chosen to encode the preferred funding source. The user can select individual bubbles to discover detailed information about a particular project.
Each bubble represents a different project or initiative. Project attributes, e.g., total cost, sponsoring organisation, and preferred funding source, are encoded by bubble size, bubble colour, and hue respectively. Bubbles with a dashed outline represent those projects that have been manually forced into or out of the portfolio by the user.

When the cursor hovers over a bubble a subset of the details about the associated project are displayed.

Bubbles cluster dynamically according to a user selectable attribute. In this instance the chosen attribute is project cost.

Bubbles can be manually dragged-and-dropped by the user to include or exclude a particular project from the portfolio.

In this instance bubbles are clustered according to the planning horizon in which the associated project is expected to begin.

Bubbles can be selected by the user in order to display even more detail about the associated project.

Each rectangle represents a different project or initiative. Like the juxtaposed bubble cluster plot, project attributes, e.g., total cost, sponsoring organisation, and preferred funding source are encoded by area, bubble colour, and hue respectively. Rectangles with a dashed outline represent those projects that have been manually forced into or out of the portfolio by the user.

The juxtaposed tree map has all of the same features as the juxtaposed bubble cluster plot, except that clusters are not labelled. To force a project into or out of the portfolio, individual rectangles can be dragged and dropped from one side of the plot to the other.

The space filling nature of the juxtaposed treemap makes it easy to see the disparity between the size of the portfolio and the aggregate size of all projects that are not in the portfolio. In this instance the attribute chosen to represent project size is project cost, and the portfolio represents only 20% of all fiscal demand associated with all potential projects.

**Figure 8:** The Visual elements of VIPOR. (a) Juxtaposed bubble-cluster plot illustrates portfolio composition via circles, (b) Juxtaposed treemap plot also illustrates portfolio composition via space filling rectangles. In both plots the user can drag and drop projects from one side to the other in order to force projects into or out of the portfolio. Note: All data in these examples are fictitious.
The bubbles themselves are dynamically attracted via a force layout algorithm so that they form clusters according to user-selectable categorical attribute. Commonly the project sponsoring organization or the categorical time horizon in which the project is expected to start are chosen as the basis for project clustering.

As the name of this plot suggests it contains two juxtaposed views: the left view contains projects that are currently part of the portfolio; the right view contains projects that are not part of the portfolio. Projects can be dragged between the two views to force them into or out of the portfolio. As projects are dragged and dropped from one side to the another they are automatically attracted to the cluster to which they belong and the outline of the corresponding bubble changes to indicate that the project’s inclusion status within the portfolio has been manually altered by the user.

The stacked bars located on each side of the plot encode either the total cost or total value of the adjacent projects. These bars update automatically as the projects are manually moved in and out of the portfolio. The stacked nature of the bars also shows the proportionality of cost or value according to a user-selectable categorical attribute. Commonly users set the categorical stacking attribute so that it is equivalent to the attribute used for bubble clustering (e.g., the project’s sponsoring organization or the categorical time horizon in which it starts).

**Juxtaposed treemap plot—Figure 8(b):** While the juxtaposed bubble-cluster plot conveniently facilitates manual alteration of a portfolio on a project-by-project basis, it is not the most viable layout for illustrating the relative differences in magnitude between projects or groups of projects. The juxtaposed treemap better enables such comparisons—individual projects are encoded by quadrilaterals within a two-level hierarchy. Similar to the juxtaposed-bubble cluster plot, the top level of the hierarchy corresponds to a user-selectable clustering attribute, and the size and colour of each project can be configured by the user to encode attributes from a selectable set. Generally the same user settings are applied to both the juxtaposed bubble-cluster plot and the treemaps.

The juxtaposed treemap is implemented as two separate treemaps, one for projects that are within the portfolio and one for projects that are out of the portfolio. A stacked bar is also associated with each treemap. The configuration of the plot can be adjusted by the user so that each treemap is equal in size, or alternately, the size of each treemap can be made to vary in proportion to the total cost or value of the projects contained within it. The former maintains a degree of spatial similarity with the juxtaposed bubble cluster plot, while the latter allows the user to see more detail about projects and their proportional sizing. Effectively, each treemap provides further resolution with regard to the information presented by the stacked bars.

Once a new user becomes comfortable with the juxtaposed bubble cluster plot, they are usually able to make an easy transition to the juxtaposed treemap because, aside from the difference between the area-filling layout of the treemap and the layout of bubble cluster
plot, the interactive features of both plots are the same. For example, projects can be selected to discover further project-related information, and they can be dragged from one side of the plot to the other to facilitate manual adjustment of the portfolio. With regard to the latter, as projects are dragged overtop of one another, slight transparency in the fill of each project rectangle is maintained. Therefore, in some circumstances users are able to make direct comparisons of project size. When projects are dropped from one side of the plot to another then both treemaps and the stacked bars are redrawn to reflect the change.

**Sets of bullet charts along a timeline—Figure 9:** A key aspect of creating a viable portfolio is to ensure that it does not violate resource constraints over its multi-year lifetime. Not only can the available supply of project delivery resources change from year to year, but the targets and thresholds that specify acceptable minimum and maximum utilization percentages for those resources can change as well. A series of bullet charts aligned along a horizontal timeline provides a space efficient way to display these annual data. In each bullet chart the length of the main bar (dark blue) encodes the quantity of resources utilized by the current portfolio. Layered behind the main bar is a secondary bar (light blue) that encodes what the total demand for resources would be in that particular year if all projects were added to the portfolio. Horizontal marks encode maximum (black) and minimum utilization thresholds (green and yellow). The lightly shaded grey bars that encapsulate the main and secondary bar in each bullet encode ordinal ratings of resource utilization performance. Other marks along the top of each bullet encode the categorical time horizon to which the bullet belongs.

All bullet charts are coordinated with the juxtaposed bubble cluster plot and the juxtaposed tree map. Therefore as projects are manually added or removed from the portfolio the bullet charts change dynamically. For example, a red bar is superimposed on top of each bullet show the proportion that has been forced manually into the portfolio by the user. Violations of maximum or minimum resource utilization thresholds are also highlighted dynamically (i.e., horizontal marks become yellow when the demand for resources is within 10% of the threshold and red when the demand exceeds the threshold). However, conformance to these utilization thresholds is only enforced during the process of mathematical optimization. As such, a user can choose to adjust either the resource supply, the thresholds governing usage of the supply, or the sizes and timings of individual projects if it becomes desirable to alleviate choke points between supply vs. demand during the iterative process of constructing a portfolio.
Figure 9: The Visual elements of VIPOR: Sets of bullet charts along a timeline illustrate the difference between the supply and demand for resources associated with a portfolio.

Note: All data in these examples are fictitious.

Configurable bubble-scatter plot—Figure 10(a): Scatter plots are a mainstay of many portfolio selection processes and VIPOR does not diverge from this trend. Similar to the juxtaposed bubble-cluster plot, VIPOR’s scatter plot is configurable by the user. By selecting from a predefined set of project attributes, the user can determine which of these will be encoded by a bubble’s size, colour, and position along the horizontal and vertical axis.

Discovery and presentation via the bubble-scatter plot is enhanced through the use of dynamic filters and the user’s ability to toggle the application of a force layout algorithm. Dynamic filtering allows the user to change certain project bubbles into small specks. These
specks reside at the correct location on the scatter plot but provide no additional visual information about projects which are not intended to attract viewer attention. The force layout algorithm helps to alleviate visual occlusion challenges in cases where many bubbles reside in a similar location. When toggled on, this algorithm attracts project bubbles toward their correct location but their final resting position on the plot is only approximate because neighbouring bubbles are not allowed to overlap. When the force layout algorithm is toggled off the bubbles are positioned accurately at the expense of potential occlusion.

Each bubble represents a different project or initiative. Project attributes, e.g., total cost, sponsoring organisation, and preferred funding source are encoded by bubble size, bubble colour, and hue respectively. Bubbles with a dashed outline represent those projects that have been manually forced into or out of the portfolio by the user.

When the cursor hovers over a bubble a subset of project attributes are displayed. Bubbles can also be selected in order to display in-depth detail about a project.

User can select to hide projects that have certain attributes. E.g., projects that have not been included in the portfolio can be shown as points whereas projects that are included in the portfolio can be shown as bubbles. In this plot no projects are hidden and all of them are shown as bubbles.

Each axis in the parallel coordinates plot represents a different project attribute. Each contiguous line that runs horizontally across the parallel coordinates plot represents a different project.

The user can use the cursor to brush each axis in order to filter (i.e., highlight) projects that have attribute values which fall within a certain range.

Projects displayed in the table correspond to those projects that have been highlighted in the parallel coordinates plot.

**Figure 10:** The Visual elements of VIPOR: (a) The configurable bubble-scatter plot is used for identifying and comparing project attributes, (b) The parallel coordinates plot is used for identifying and characterizing project attributes. Note: All data in these examples are fictitious.
The starting configuration of the bubble-scatter plot, from which a user makes adjustments, was determined via user trials as follows: filters are set to show only those projects that are in the portfolio; the force layout algorithm is turned on; project value is encoded by position along the horizontal axis; project cost is encoded by both the size of the bubble and its position along the vertical axis, and the sponsoring organization for each project is encoded by bubble colour.

Parallel coordinate plot of project details—Figure 10(b): Whereas the configurable bubble-scatter plot facilitates analysis of correlations and the identification of project clusters based on two project attributes, the parallel coordinate plot enables analysis across several project attributes at the same time. These attributes include the various types of project cost, project scores against the different value criteria, and categorical attributes like project sponsor and the time horizon associated with each project. Binary attributes, including an inclusion attribute which indicates if the project is currently in or out of the portfolio, are also accessible from the parallel coordinate plot. The order of the axes on the plot is configurable by the user to facilitate visual assessments of correlation between particular project attributes.

Coordinated below the parallel coordinate plot is a table that lists individual projects and their associated attribute values. By brushing portions of each parallel axes a user is able to filter the set of projects that appear in the table. Likewise, by selecting a project in the table, the values of its attributes are demarcated in the parallel coordinate plot and this facilitates easy comparison against the population of other projects. Projects can also be manually included or excluded from the portfolio via altering their attributes within the coordinated table.

Modal dialogue of project details: Often hundreds of potential projects spanning across many sponsoring organizations must be considered within the portfolio construction process. It is therefore necessary to have the ability to recall both structured and unstructured information pertaining to individual projects. A modal dialogue (not shown here) that contains project text descriptions, sponsor annotations, cost profiles, value scores, and other derived information fulfills this need. This modal dialogue also enables the user to change certain key data pertaining to a project, including the preferred funding source, the preferred start year for the project, and whether it should be forced into or out of the portfolio. The modal dialogue is exposed when a graphical element which encodes a particular project is selected by the user from any other plot.

Project inclusion sensitivity triangle—Figure 11: The project details modal dialogue contains several graphical elements. One of these is a triangular graph that presents the degree with which a project’s inclusion in the portfolio is sensitive to the weight factors applied to each of the criteria used in the computation of overall project value. The sensitivity triangle has utility for some users when they are contemplating decisions to manually force projects into or out of the portfolio. Users are first introduced to the triangle concept
when they encounter the control interface, where a point within a similar triangle encodes the combination of weight factors chosen by the user to determine the overall value of each project.

Each corner of the triangle is associated with one of the three criteria. The edges and inner area of the triangle represent the space of possible criteria weight combinations. The vertices of the triangle encode cases where all of the weight is assigned to the associated criterion and the remaining criteria have no influence on the overall value of the project. At points inside the triangle the proximity to each vertex is proportional to the weight assigned to associated criteria. The shorter the distance between the point and the vertex the greater the weight given to the associated criteria. VIPOR samples 64 different points within the triangle. Contours of total project score based on computed results for these 64 points are encoded by graduating the luminance in the fill of the triangle. Then, based on the weights associated with each point, VIPOR’s optimization algorithm is used to compute whether the project would be included in the portfolio. Points within the triangle are coloured green if the project would be included, and black if it would not. Also computed is the inclusion percentage for each project across all combinations of weights.

![Diagram of VIPOR interface](image)

**Figure 11:** The Visual elements of VIPOR: (a) Criteria weight settings triangle, and (b) Project inclusion sensitivity triangle. Note: All data in these examples are fictitious.

**Figure 12(a):** An ability to visually trace the changes in a portfolio throughout the iterative construction process is useful, not
only because having transparency about project inclusion decisions is a necessary part of portfolio management, but because it helps facilitate an enhanced understanding of opportunity cost. As projects are manually added and removed from a portfolio by a user, other projects are often added and removed from the portfolio by the optimization algorithm in order to ensure that portfolio construction constraints are not violated. The heatmap highlights these alterations.

Each row in the heatmap represents a particular project, and each column represents an iteration in the portfolio construction process. Green squares at the row-column intersections encode projects that are included in the portfolio while black squares encode projects that are not included in the portfolio. Red borders around particular squares identify those projects that have been manually included or removed from the portfolio by the user. Within the heatmap individual rows can be sorted based on one or more selectable attributes in order to enable comparisons of similar projects all iterations. The ordering of the columns can also be manually adjusted to facilitate a side-by-side comparison of project inclusion for non-successive iterations in the portfolio construction process.

Scatter plot of portfolio value by iteration—Figure 12(b): During the iterative portfolio construction process it is useful to track and understand how the overall value of the portfolio changes as adjustments are made. A scatter plot with the iteration number encoded along the horizontal axis and the total value of the portfolio encoded along the vertical axis fulfills this need. On this scatter plot three series of data points are superimposed as follows. The first series of points (horizontal solid black line), computed in accordance with the selected combination of criteria weights, illustrates the aggregate value of all projects under consideration, regardless of whether they are in the portfolio or not. The second series of points (horizontal dashed line) indicates the value of the optimal portfolio. The third series of contains two sets of points: the black dots correspond to the non-integer solution provided by the simplex algorithm, and the red dots that correspond to the integer solution provided by the branch and bound algorithm.
Figure 12: The Visual elements of VIPOR: (a) Heatmap of portfolio composition by iteration, (b) Scatter plot of portfolio value by iteration. Note: All data in these examples are fictitious.
8 Example work flow

In this section we briefly demonstrate, through a hypothetical scenario, how a user might
progress through the iterative construction of a portfolio. For purposes of clarity, we use
italics to highlight both the high-level subtasks and the individual visual elements of VIPOR.
We also make reference to the overview of visual elements shown in figure Figure 13 so
that the reader can more easily follow the progression.

Note that although the size of the data sets used in VIPOR vary, typically they contain
hundreds projects, with one to three variants per project and funding requirements on the
order of millions of dollars over a 1–20 year period. As such, the there is wide variation
in how the construction process could unfold. What follows is one instantiation of this
process.

Initial construction of a portfolio: The Set Parameters menu shown in Figure 7 facilitates
the start of the iterative portfolio construction process. The user selects the Run Algorithm
menu to trigger construction of the portfolio, but only after project data is loaded, criteria
weights are set, portfolio constraints are determined, and optimization algorithm para-
eters are configured. After the portfolio is created, the majority of our user’s interaction with
VIPOR occurs through the visualizations.

Characterize portfolio composition: Assuming that the portfolio construction problem
remains well posed, the next task is to characterize portfolio composition. To perform this
task our user navigates to the juxtaposed bubble clusters plot (i.e., Figure 13(a)), deter-
mines whether the standard configuration of this plot is adequate for initial analysis (e.g.,
projects are clustered by sponsoring organization, bubble size encodes project cost) and
make adjustments to the configuration to best suit their preferences.

A comparison of the stacked bars makes it immediately evident that the total expenditure
for projects included within the portfolio is much less than the total cost associated with
those projects not included in the portfolio. This observation is confirmed by temporarily
navigating to the juxtaposed treemap plot (i.e., Figure 13(b)). Examination of these two
plots also makes it clear that only a few high-cost projects have been included in the port-
folio, and that the exclusion of high-cost projects does not seem to correlate strongly with
sponsoring organization.

To better understand the conditions surrounding the exclusion of high-cost projects, our
user changes the clustering parameter from ‘sponsoring organization’ to ‘time horizon’ in the
juxtaposed bubble-cluster plot. The updated visualization indicates that many high-cost
projects excluded from the portfolio are set to begin within the same categorical planning
horizon. With this information in hand, our user wants a closer examination of resource
utilization across time.
Figure 13: An overview of the visual elements of VIPOR. (a) Juxtaposed bubble-cluster plot illustrates portfolio composition, (b) Juxtaposed treemap plot also illustrates portfolio composition, (c) Sets of bullet charts along a timeline illustrate resource consumption, (d) Configurable bubble-scatter plot is used for identifying and comparing project attributes, (e) Parallel coordinates plot is used for identifying and characterizing project attributes, (f) Criteria weight settings triangle and Project inclusion sensitivity triangle, (g) Heatmap of portfolio composition by iteration, (h) Scatter plot of portfolio value by iteration. Note: All data in these examples are fictitious.
Characterize resource utilization: Characterization of resource utilization across time is best accomplished by assessing bullet charts like the one presented in Figure 13(c). Using this visualization, our user examines the available resources for delivering projects, as well as resource utilization by projects in the portfolio. This examination indicates that while resources remain available to deliver projects certain fiscal years, funds are used up by the portfolio in every year between 2021 and 2025. In contrast, the user observes that in future time horizons the available fiscal supply is not fully consumed. From this observation the user hypothesizes that high-cost projects may not be included in the portfolio because their benefits do not justify their costs during the periods when there is a lot of competition for financial resources.

Characterize projects: To verify his hypothesis our user requires further information about the projects. This is obtained by navigating to the bubble-scatter plot (Figure 13(d)) and configuring it so that project cost is plotted against project value. By inspecting the result it becomes clear that several high-cost projects have higher scores than some of the lower-cost projects which are included in the portfolio. To understand this dynamic the user selects individual high-cost projects from within the bubble-scatter plot to expose the project details modal view. This view exposes individual cost profiles and the project inclusion sensitivity triangles (e.g., Figure 13(f)). From these it becomes clear that the inclusion of very high-cost projects in the portfolio is sensitive to both the preferred start date of the project and the weight assigned to the three criteria used to determine project’s overall value. Mindful of these facts, our user decides to adjust the portfolio by forcing at least one of the high-cost projects into the portfolio.

Adjust the portfolio: To identify which of the high-cost projects should be forced into the portfolio first, the user navigates to the parallel coordinate plot (Figure 13(e)); brushes the cost axis to identify the high-cost projects under consideration; and compares their costs, start dates, and individual scores against the three value criteria. By undertaking these comparisons our user decides to force a high-cost project into the portfolio that has a preferred start date of 2024, a relatively low cost compared to other high-cost projects, and a high National policy alignment score.

To implement this adjustment our user navigates to the juxtaposed treemap plot (Figure 13(b)) and drags the project into the portfolio. As the user drags the project, the superposition of this project on top of those already in the portfolio makes it visually evident that, due to the high-cost of the project being forced into the portfolio, five or more other low-cost projects will likely need to be removed from the portfolio in order that it remain in compliance with resource constraints.

Our user could try to select and remove these projects manually, but instead decides that it would be more efficient to allow the optimization algorithm to determine the best set of projects to displace from the portfolio. But before doing so our user recalls that there are a few projects that must remain within the portfolio. To facilitate his recollection our user
returns to the parallel coordinates plot (Figure 13(e)); brushes both the project sponsor axis and the project inclusion axis; and uses the coordinated table below the parallel coordinates plot to select those projects that must remain in the portfolio when it is recomputed. The user then selects Run algorithm to execute the portfolio construction model, and the return of its result begins the next iteration of the portfolio construction process.

**Compare portfolios:** To begin the next iteration of portfolio development, our user compares the previous and current portfolio. The heatmap of portfolio composition, like the one presented in Figure 13(g), is used for this purpose. An assessment of this heatmap indicates that all projects which were manually forced into the portfolio by the user have indeed become part of the portfolio. However, it becomes clear to our user that the process of forcing projects into the portfolio has resulted in the displacement of eight projects. Next, by navigating to the scatter plot of portfolio value by iteration, an example of which is shown in Figure 13(h), our user determines that the aggregate impact of these adjustments on the total value of the portfolio is relatively small. After navigating back to the heatmap of portfolio composition and exposing the details about the displaced projects our user decides that its acceptable to remove these projects from the portfolio. The portfolio is then presented to senior level decision-makers for subsequent deliberation.
9 Implementation

As a web application, VIPOR’s visualizations have been written in JavaScript using D3.js [50] and its layout is achieved using Twitter’s Bootstrap framework\(^2\). The portfolio optimization model was implemented using GNU MathProg (GMPL)\(^3\), an open source version of the AMPL [51] modelling language that is intended for linear and mixed integer mathematical programming models.

When a user triggers re-optimization of a portfolio, the client-side JavaScript code sends a web service request to a PHP backend. In sequence, this backend: (1) writes a GMPL model file based on user preferences; (2) creates an R script that reads the GMPL model file, converts user preferences into constraints, and adds the constraints to the optimization model; (3) calls the GNU Linear Programming Kit. GNU is a recursive acronym for: GNU’s Not Unix. The GNU project is a mass collaborative initiative for the development of free software. (GLPK) to compute the relaxed Linear Programming (LP) solution and the best integer solution; and (4) processes the results and returns the solutions to the client-side code.

We tested VIPOR using many different data sets, ranging in size from tens of projects to several hundred projects. Based on our experience, these test cases are representative of the scope of real portfolio construction problems. For all data sets tested, we found the user interface to be responsive and the application was able to produce viable portfolios in accordance with time limits set by the user when running on a client-side desktop PC (e.g., Intel i7 CPU, 2.13 GHz, 4 GB RAM) and a server (e.g., Intel Xeon CPU, 2.4 GHz, 144 GB RAM).

\(^2\) See getbootstrap.com
\(^3\) See www.gnu.org/software/glpk/
Evaluation of decision support systems that utilize information visualizations can occur in various stages of development, such as design or deployment, and under different scenarios [52]. These scenarios, as suggested by Lam et al., can be broadly classified into two groups: process, aimed at a holistic view of the user experience, and visualization, focused on design decisions, bench-marking against existing systems, discovering usability issues, etc. Given the practical context in which VIPOR was developed, our evaluation focused on its deployment stage—a real-world assessment of VIPOR’s holistic benefit to support Defence’s investment planning process—and our evaluation goals centered on three process related questions.

1. Would VIPOR help experts to see the investment planning problem differently?

2. Would VIPOR help to perform investment planning tasks faster, more correctly, and with less workload?

3. What was the degree with which VIPOR was adopted across Defence in support of the portfolio construction paradigm that it promotes?

There are many approaches—controlled laboratory experiments, interviews, case studies, value-driven, etc.—that may be used to answer these questions [52, 53, 54, 55, 56]. We elected to conduct a value-driven evaluation through a case study. We collected data through observations and interviews, rather than other means such as surveys, for two reasons. First, the turnover of civilian staff and the frequency with which military members post to different positions limited the design team’s access to people with in-depth experience with previous planning cycles. This made approaches that compare VIPOR with previous decision support efforts infeasible. Second, the resources required to execute two parallel investment planning processes—one using the ranked list approach and one using VIPOR—were not available due to the extra demand that would be placed upon staff.

Data: VIPOR’s evaluation occurred during Defence’s recent CIPPR initiative. Within this effort, data regarding approximately 350 projects, each having up to three variants, were collected. The cumulative fiscal demand of these projects was on the order of tens of billions of dollars across a time frame of approximately 40 years. Information about each project was collected from and approved by its sponsoring organization. As such, many business analysts and decision-makers were familiar with their own organization’s projects, but not necessarily those from other organizations.

Participants: We observed and interviewed both analysts and decision-makers on an intermittent basis during a 16 month period.

- Analysts: This group consisted of approximately 25 individuals from across Defence. Analysts had either military or civilian background and varying degrees of experience.
with extant Defence investment planning processes. This group was further divided into two subgroups: the first was a subgroup of approximately five analysts that were assigned to coordinate and facilitate the investment planning process; the second subgroup consisted of 20 analysts that were assigned to provide support to their respective organizations during the investment planning process. The first subgroup was expected to use VIPOR extensively, provide briefings on VIPOR to other analysts, and present analyses to decision-makers. The second subgroup did not use VIPOR directly, however did receive comprehensive briefings on VIPOR, its functionality, and its role within the portfolio construction process.

- **Decision-makers**: This group consisted of approximately five decision-makers, including those at the highest executive levels of several internal organizations across Defence. This group received regular briefings from analysts. These briefings focused on either VIPOR’s design, the planning tasks it was designed to facilitate, or the results that it produced.

The design team collected feedback during briefings and through one-on-one unstructured interviews with members of from each group. From the first subgroup of analysts we observed how VIPOR was actually being used, and from the second subgroup of analysts we collected feedback about VIPOR’s functionality and the results it produced. For the decision-maker group, we noted their reactions and feedback, and we observed the directions they gave to analysts during executive briefings.

**Results**: Regarding the ability of VIPOR to help users to see the defence investment planning problem differently, we noted early during the assessment period that both analysts and decision-makers began referring to a set of projects as a ‘portfolio’ rather than as a ‘ranked list’, and that there were fewer mentions of a ‘cut-line’ which would determine which projects would be selected.

Subsequent observations during the assessment period suggested that this shift in mindset was facilitated by VIPOR’s integration of visualization, portfolio optimization and interactivity to facilitate improved user understanding and iterative adjustment of the portfolio. For example, we observed that the juxtaposed bubble cluster plot and the juxtaposed treemap, which gave the user an ability to cluster projects based on different attributes, helped them to consider the portfolio as a holistic collection rather than a ranked list. In addition, allowing users to make manual adjustments using these same plots and then allowing them to trigger a mathematical optimization algorithm to realize subsequent alterations in accordance with practical constraints, instilled confidence in the portfolio construction approach. It also emphasized the notion that viable portfolios represent a balance between many factors over time. This concept of balance also became increasingly apparent to users as they assessed follow-on effects of their manual adjustments via the portfolio composition heatmap. Given that during the assessment period both analysts and decision-makers did not revert back to describing Defence’s investment plan as a ranked list of projects,
there is evidence that VIPOR has helped users see the defence investment planning problem differently.

Our second evaluation component was to determine if users could perform tasks more efficiently and effectively. In this regard, we observed that the construction, characterization, and adjustment tasks were performed in hours, rather than weeks as typically required when using the ranked list approach. This is due in part to that VIPOR combines disparate critical information into one application. In contrast, many critical data were held in separate locations during previous planning processes and these data were not easily accessible to analytical applications being used by different internal organizations. As such, the portfolio construction process was not agile and it took a long period of time to determine which projects should be added or removed when attempting to create the greatest organizational value without contravening financial, capacity, and other constraints. In this regard, VIPOR was able to facilitate a more efficient decision cycle. For example, in one instance shortly after the first prototype of VIPOR was delivered, it became necessary to investigate the viability of a time-sensitive opportunity to undertake a new major capital acquisition with significant strategic implications. Because of the ease with which VIPOR was able to ingest new project information, and because of VIPOR’s ability to help assess the impacts of including the new project in the portfolio, the team conducting the analysis was able to inform this investment decision in a timely way.

Our third evaluation question was to gauge the adoption of VIPOR by both analysts and decision-makers. In this regard, we found that throughout the entire assessment period both of these groups were very willing to make use of VIPOR and/or its results in order to inform investment decisions and enhance decision-making processes. Two years after the VIPOR’s introduction, it has become an important analytical element of Defence’s evolving portfolio management approach.
11 Future considerations

It was observed that the use of VIPOR led analysts and decision-makers to ask new questions, such as “If it were possible, how should the available financial envelopes be re-profiled over time in order to better accommodate projected demands?” and “What is the optimal proportion of the available financial resources should remain unallocated?” Questions like these provide evidence that VIPOR has helped to improve the level of collective organizational understanding about portfolio construction. Moreover, with this improved understanding, the appetite to advance the analytical component of portfolio construction further has grown since VIPOR was introduced. In response, near-term developments to further enhance the utility of VIPOR have been categorized as follows.

- **Visual methods that further enhance the user’s ability to manually adjust the supply and demand for resources, and to specify acceptable ranges or degrees of uncertainty associated with these.** This development category includes, for example, new features to create or modify alternative resource demand profiles for individual projects. It also includes the addition of new features that will make it easier for a user to make intricate adjustments to the supply of available resources and to specify the degree to which it is acceptable to violate resource supply constraints.

- **Visual methods that enhance how a user understands the degree of balance that is achieved by different portfolios.** This includes, for example, improved methods to visualize the many-to-many relationships and to explore the linkages between a chosen portfolio and several strategic factors including: government policy announcements, strategic objectives, military capability profiles, and organizational performance targets.

- **Visual methods that further enhance the ability to compare alternative portfolios.** Whereas in the current version of VIPOR the focus of portfolio comparison has been on differences pertaining to project composition, there are several other portfolio attributes that, if compared, would serve to enhance the decision-making process even further. Comparing aggregate risk statistics which are computed according to a standard set of risk dimensions is just one avenue for further investigation.

- **Visual methods to facilitate the calibration of project value.** VIPOR uses a linear model as the measurable value function to compute projects value [57]. Changing the measurable value function can have a dramatic impact on which projects are selected in a portfolio. An improved visual interface that allows decision-makers to set, modify, and calibrate these value functions, and subsequently understand their impact within the optimization process, could help to improve and/or provide more confidence about the model that VIPOR employs to determine the merits of potential projects.

Presently, initial work is under way to develop a new version of VIPOR that is not like the prototype. Instead of hardwiring a single mathematical model to a fixed database and set of visualizations, a new version of VIPOR is envisioned to become a flexible platform by
which increasingly sophisticated models, data sets, and visualizations can be incorporated. For example, models could be designed to accommodate the following enhancements:

- optimize the portfolio by explicitly maximizing coverage within a set of military and institutional capabilities [58];
- consider project portfolios in terms of the financial concept of real options [59, 60];
- facilitate recursive rather than myopic decision approaches and include stochastic and dynamic programming concepts [61];
- account for uncertainty when specifying model parameters and computing project portfolios;
- ensure a controllable level of persistence between portfolios as new projects are added or removed [62];
- incorporate risk; and
- incorporate more sophisticated normalization (e.g., discounting) schemes when computing future project costs and benefits.

With a new VIPOR platform more sophisticated models enhancements such as these should be easier to implement, integrate and compare. The expected benefit of pursuing more advanced modelling concepts (many of which require more sophisticated data and an enhanced understanding project portfolio management) will be more impact to strategic decision making than what is currently afforded by VIPOR. In the meantime, it remains important that the current version of VIPOR continues to satisfy its original compliance aims, ensure traceability of decisions, provide an informative and interactive visual presentation, and retain a suitable degree of understanding and simplicity among analysts and decision makers in terms of its overall construction and the underlying iterative analyses that it facilitates.
12 Summary

VIPOR was developed to support analysts and decision-makers undertaking enterprise-wide investment planning processes within a large government organization. The main impetus behind its development was to support an initial transition from a ranked list approach to a more holistic portfolio approach when determining the most viable set of projects to include within the investment plan. To this end VIPOR integrates the computational power of optimization with the power of human judgment. With this decision support system analysts and decision-makers are able to construct, characterize and interactively adjust a portfolio in an iterative fashion, and gain insight into the opportunity costs of their decisions. Fulfillment of the design goals for VIPOR were heavily dependent on its visual elements and their integrated usage within a nominal workflow.

In the first two years since its introduction, VIPOR has been embraced by both analysts and decision-makers within the Canadian Department of National Defence. Although more formal evaluation is required, observations of VIPOR’s initial use have helped to validate its design as well as identify avenues for future enhancement as Defence continues to tailor how it implements portfolio management concepts in accordance with its evolving needs.
References


Studies in Information Visualization: Seven Scenarios. *IEEE Transactions on

Proceedings of the Working Conference on Advanced Visual Interfaces, AVI ’04,
pp. 109–116, New York, NY, USA: ACM.

Visualization Tools: Multi-dimensional In-depth Long-term Case Studies, In
Proceedings of the 2006 AVI Workshop on BEyond Time and Errors: Novel
Evaluation Methods for Information Visualization, BELIV ’06, pp. 1–7, New York,
NY, USA: ACM.

of Lecture Notes in Computer Science, pp. 19–45, Springer Berlin Heidelberg.

Fifth Workshop on Beyond Time and Errors: Novel Evaluation Methods for
Visualization, BELIV ’14, pp. 46–53, New York, NY, USA: ACM.

with Spreadsheets, Toronto: Duxbury Press.

[58] Khuller, S., Moss, A., and Noar, J. (1999), The budgeted maximum coverage

University Press.


[61] Powell, W. (2007), Approximate Dynamic Programming: Solving the Curses of

[62] G.H. van Bavel (2017), Portfolio construction and persistence,
DRDC-RDDC-2017-R086, Defence Research and Development Canada, Centre for
Operational Research and Analysis.
Acronyms

**CIPPR**  Capital Investment Program Plan Review

**GLPK**  A GNU Linear Programming Kit. GNU is a recursive acronym for: GNU’s Not Unix. The GNU project is a mass collaborative initiative for the development of free software.

**GMPL**  GNU MathProg

**LP**  Linear Programming

**VIPOR**  Visual Investment Planning Optimization & Revision
<table>
<thead>
<tr>
<th>DOCUMENT CONTROL DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. ORIGINATOR</strong></td>
</tr>
<tr>
<td>(The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.)</td>
</tr>
<tr>
<td>DRDC – Centre for Operational Research and Analysis</td>
</tr>
<tr>
<td>Dept. of National Defence, MGen G. R. Pearkes</td>
</tr>
<tr>
<td>Bldg., 101 Colonel By Drive, 6CBS, Ottawa</td>
</tr>
<tr>
<td>ON K1A 0K2, Canada</td>
</tr>
<tr>
<td><strong>3. TITLE</strong></td>
</tr>
<tr>
<td>(The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)</td>
</tr>
<tr>
<td>VIPOR: A Visual Analytics Decision Support Tool for Capital Investment Planning</td>
</tr>
<tr>
<td><strong>4. AUTHORS</strong></td>
</tr>
<tr>
<td>(Last name, followed by initials – ranks, titles, etc. not to be used.)</td>
</tr>
<tr>
<td><strong>5. DATE OF PUBLICATION</strong></td>
</tr>
<tr>
<td>(Month and year of publication of document.)</td>
</tr>
<tr>
<td><strong>7. DESCRIPTIVE NOTES</strong></td>
</tr>
<tr>
<td>(The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)</td>
</tr>
<tr>
<td><strong>8. SPONSORING ACTIVITY</strong></td>
</tr>
<tr>
<td>(The name of the department project office or laboratory sponsoring the research and development – include address.)</td>
</tr>
<tr>
<td>Dept. of National Defence, MGen G. R. Pearkes Bldg., 101 Colonel By Drive, 6CBS, Ottawa</td>
</tr>
<tr>
<td><strong>9a. PROJECT OR GRANT NO.</strong></td>
</tr>
<tr>
<td>(If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)</td>
</tr>
<tr>
<td><strong>10a. ORIGINATOR'S DOCUMENT NUMBER</strong></td>
</tr>
<tr>
<td>(The official document number by which the document is identified by the originating activity. This number must be unique to this document.)</td>
</tr>
<tr>
<td><strong>11. DOCUMENT AVAILABILITY</strong></td>
</tr>
<tr>
<td>(Any limitations on further dissemination of the document, other than those imposed by security classification.)</td>
</tr>
<tr>
<td><strong>12. DOCUMENT ANNOUNCEMENT</strong></td>
</tr>
<tr>
<td>(Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11)) is possible, a wider announcement audience may be selected.)</td>
</tr>
</tbody>
</table>
Investment planning within a large public sector enterprise is often a complex process that requires considering hundreds of potential projects and millions of taxpayer dollars. The nature of this problem demands a portfolio optimization approach to generate a high quality investment plan. However, an optimization model alone is insufficient to support management decisions. Decision-makers need the ability to understand the portfolios generated by an optimization model and the underlying trade-offs that these portfolios contain. This article introduces a visual analytics decision support software called VIPOR which is an acronym for VIPOR. This software was developed to support the formulation of investment portfolios within the Department of National Defence and Canadian Armed Forces. It integrates a portfolio optimization model and several interactive information visualizations. Together, these allow for the construction, characterization, and adjustment of an investment portfolio in accordance with decision-maker preferences and practical constraints. In this report we: (1) characterize some of the necessary tasks to facilitate investment planning within a large organization that is making a shift toward a portfolio approach; (2) provide an overview of VIPOR and a description of how it can be used to build alternative portfolios; and (3) outline observations about the utility of this decision support system during the two years since its development.

Investment planning; portfolio management; visual analytics; optimization; decision support system