Investigating the Impact of Project Dependencies on Capital Investment Decisions in Defence

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ABSTRACT

The strategic planning processes that support decisions on major investments in the Canadian Department of National Defence begin with capability-based planning which informs future capability plans and results in the Defence Investment Plan. The processes that identify capability gaps and generate new project plans are not the subject of this study. This study is about the process used by strategic planners to select a portfolio of investments from these new project plans and considers how a portfolio of projects may be affected if project relationships and dependencies are used in that process.

In this investigation, analysts were provided access to a dataset with information collected from a large number of the major capital projects in the department. The collection included responses to specific questions on the relationships between projects. The analysis investigated the impact of these relationships on the construction of portfolios of projects using a new tool called SPARC, the Strategic Portfolio Analyser with Reconfigurable Components. SPARC, developed for Defence Research and Development Canada by the National Research Council of Canada, provides the capability to import a wide variety of datasets, analyse portfolios of projects using optimization algorithms, and view the results using interactive visualizations. This paper documents the analysis that was conducted on the dataset of major capital projects and describes the tool, SPARC, that was used for the investigation.

KEYWORDS

SPARC, Portfolio Optimization, Major Project Relationships, Capital Investment Planning

1.0 INTRODUCTION

A key activity in the Department of National Defence (DND) is the planning and implementation of major capital projects. This is a critical part of maintaining a modern and effective military force. The demand from proposed projects is always greater than the budget and DND employs a portfolio management process, the Capital Investment Program Plan Review (CIPPR), to select the best set of projects to fit the planned budget. This process is informed by Capability-Based Planning (CBP) [1]. Both planning activities are conducted by the staff in the Chief of Force Development (CFD) organization whose mission is to “harmonize, synchronize and integrate the force development activities of the Canadian Armed Forces (CAF)” (quote from the CFD Mandate) [2].

Project portfolio management is an important business process in many large organizations. In the business of defence, there have been many interesting implementations. A classic force development example from South Africa: “Guns or Butter: Decision Support for Determining the Size and Shape of the South African National Defense Force” [3] was published in 1997. This was an early example of the use of a mixed integer program to perform an optimization to inform decisions in strategic force development. The calculations were performed in the mid 1990's on a Pentium PC where optimal solutions were initially being generated in days and eventually in hours. Twenty-five years later, we are unhappy if a solution takes more than a few minutes!

A paper presented by Defence Research and Development Canada (DRDC) at the 2019 NATO Operational Research and Analysis (OR&A) Conference [4] discussed current portfolio analysis practices employed by CFD to support the CIPPR process and proposed research on the value of including project relationships or dependencies in the planning of defence portfolios. That paper looked at some of the challenges in defining value for diverse projects with relationships or dependencies and proposed an interdependency framework as well as an Artificial Intelligence (AI) methodology for processing project documents and other information sources.

Insights on how NATO, Partnership-for-Peace, and Enhanced Opportunities nations prioritize their defence strategic investments, may be found in the final report of the NATO SAS-134[1] Research Task Group (RTG) [5]. In a summary of the findings of a survey by the SAS-134 RTG, presented at the 2022 NATO OR&A Conference [6], it was reported that the responding nations conduct investment portfolio planning and employ strategies to optimize the benefits.

This paper focusses on the use of mathematical optimization for project portfolio management. DRDC developed the prototype for a tool used by CFD called VIPOR (Visual Investment Planning Optimization & Revision) [7] which has been used in the past to perform portfolio optimization calculations for CIPPR. This software tool may be used for binary (or 0-1) multiple knapsack problems with multiple constraints. This tool can model plans for major defence projects over a period of years where the planned budgets provide annual constraints. This model also supports dependencies between projects; if there is a relationship between two projects such that A depends upon B, the algorithm will select B with A. VIPOR also has interactive visualizations to aid the user in exploring alternatives. One of VIPOR's best features is that it provides a capability to review a potential portfolio of projects, make adjustments to the portfolio, and then re-optimize the portfolio without leaving the user interface. Based upon the success of VIPOR, DRDC began a project in 2017 to create a generic version of this software – the Strategic Portfolio Analyser with Re-configurable Components (SPARC) [8].

This paper investigates the question: how is a portfolio of projects affected if project dependencies are used in the optimization process? The next section describes the new tool, SPARC, focussing on the most recent additions which are algorithms to process project interdependency information. The data collection for the case study used in this paper is discussed in section three. Then, in section four, the analysis is presented documenting the impact of project dependencies on the calculation of optimal portfolios of major capital projects.

2.0 STRATEGIC PORTFOLIO ANALYZER WITH RE-CONFIGURABLE COMPONENTS (SPARC)

The SPARC software is a decision support tool developed by DRDC's Centre for Operational Research and Analysis (CORA) in collaboration with the National Research Council of Canada (NRC). The software is designed to provide interactive portfolio optimization and visualization capabilities to an analyst or an analyst-supported, non-technical user. SPARC can be used to explore trade-offs in portfolio decisions or view the effects of different scenarios on portfolio solutions.

SPARC is integrated with commercial optimization software: CPLEX [9], SAS 9.4 [10], SCIP [11] version 6.0.2, and a customized solver based upon MATLAB [12]. Good optimization software is necessary for interactive use which requires solutions be found in near-real time. These software selections were made based

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[1] NATO SAS-134: Improving Defence Investment Portfolio Decisions: Insights from the Literature and National Practice.

upon a benchmarking study [13] performed with a set of project portfolio problems similar in size and complexity to the CIPPR dataset prepared by CFD annually. The customized solver option was developed by researchers at DRDC [14] and is based on the MATLAB Optimization Toolbox. It relies on the MATLAB Runtime [15] set of shared libraries.

2.1 Interdependencies Algorithm

SPARC has several portfolio optimization algorithms. This paper focuses on the interdependencies algorithm. This algorithm is based on a binary knapsack where the algorithm makes decisions to include or exclude a project from the portfolio solution and the objective is to maximize the total value of the portfolio. The dependencies used are directed relationships between projects. Each dependency is defined using two parameters to describe the relationship.

The first parameter is the dependency strength, which can be one of three levels: strong, medium, and weak. This defines how dependent a given project may be upon another. The second parameter is the dependency synergy. The synergy acts as a multiplier on the value of the primary project when the secondary project is also selected. If there are multiple synergistic relationships originating from the primary project, then the synergy multiplier is averaged across all applicable relationships and then multiplied on the value of the primary project. Currently, a dependent relationship is required to apply synergistic effects.

The interdependency algorithm works by pre-processing all dependencies to form sets of dependency bundles before performing the binary knapsack optimization. Constraints are also added to the optimization model such that only one version of a project may be selected if they exist in multiple bundles. Before optimizing, the user selects the minimum level of dependency strength to include in the optimization. The pre-processing then only applies dependencies that are within the specified dependency range, therefore forming or breaking bonds as specified by the user. Synergistic effects are also applied to any relationships that are included in the optimization. This allows the user to create portfolios with alternative dependency levels and view the effects of forming or breaking dependencies on the overall portfolio performance. This algorithm is described in more detail in [16] and [17].

2.2 Interactive Visualizations

A set of interactive visualizations are included in SPARC to allow the user to quickly review and evaluate results. This creates an engaging environment for analysts or decision makers where they can pick out trends, make comparisons between portfolio results, and explore options. The options for interacting with the visualizations include:

- Forcing projects into, or out of, a portfolio (creating a constraint in the knapsack model).
- Updating visuals to including categorical clustering or re-sizing elements according to numerical data.
- Using project data pop-ups to provide detailed information about a specific project.
- Editing project or portfolio data from the user interface; and
- Re-solving the portfolio after an interaction or series of interactions.

As SPARC was designed to function with a variety of datasets, the collection of visualizations in SPARC includes visualizations that are best used for certain types of data. This provides analysts with a variety of options to select from to best display and explore the different types of data within their dataset. Figure 1 shows the SPARC interface with the bubble chart visualization for a portfolio of major capital investments where no dependencies are included. The user can select different display options from the top menu to modify the display of the information. The user can also click and drag bubbles to force projects in or out of the portfolio. If the user right clicks on a bubble a pop-up is produced displaying detailed project information.

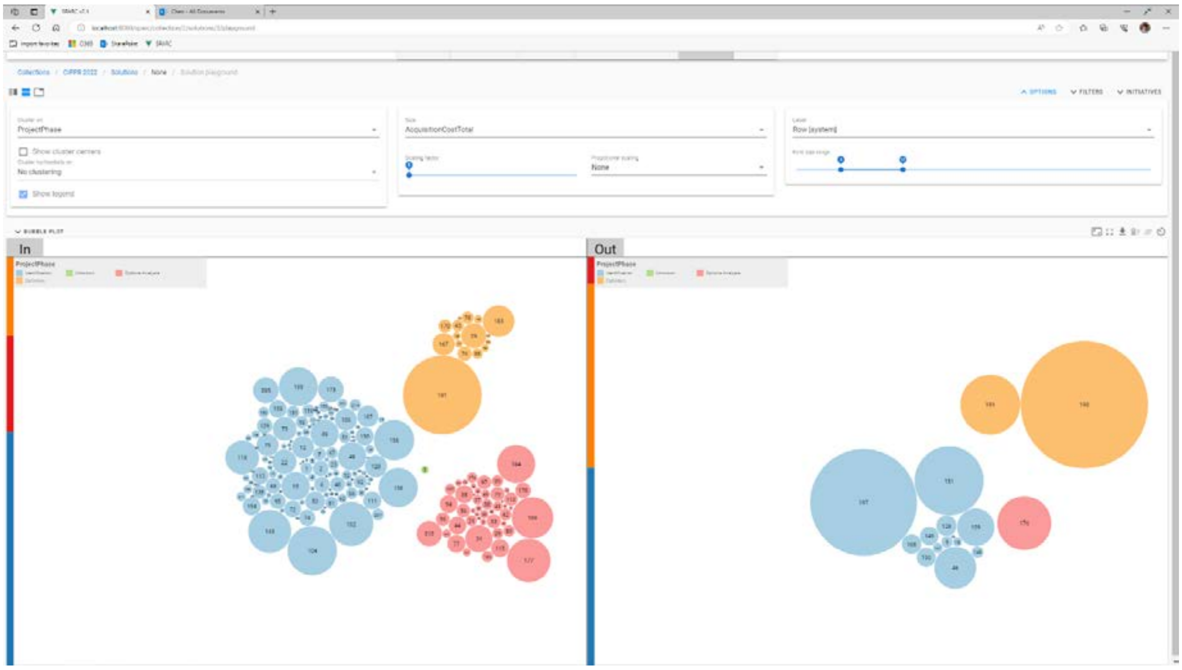

Figure 1: SPARC bubble chart interface displaying the results for a portfolio with no dependencies. Bubbles are sized based on their total cost. Bubble colour represents the project phase where Blue is Identification, Red is Options Analysis, Orange is Definition and Green is Unknown. The left side of the chart includes all projects that are in the portfolio, and the right side of the chart includes all projects that are left out of the portfolio.

3.0 DATA COLLECTION

This analysis used data extracted from the database for major capital projects in the Canadian Department of National Defence. The data was collected using a Microsoft InfoPath questionnaire that was filled out by project sponsors. A total of 215 projects were used in the analysis.

Project relationships data was specifically collected as a part of the questionnaire in 2022. Each relationship was defined as a one-way (or directed) relationship, where the primary project is the project submitting the data. Project managers were able to list each related project using five pre-defined relationships. The five types of relationships were defined as:

- Cost benefit – by selecting both projects the overall cost will be lower.
- Scheduling benefit – by selecting both projects the projects benefits will be accrued more quickly.
- Qualitative benefit – by selecting both projects the total value of the projects increases.
- Quantitative benefit – by selecting both projects manufacturers, are able to provide additional units for the same price.
- Cannot succeed – both projects must be selected together.

Each project manager can submit multiple relationships for each related, or secondary, project. Relationship data was processed and cleaned to remove any references to projects outside of the list of projects used in this analysis.

The first four relationships define synergistic dependencies where there is improvement in results if the projects are selected together. These relationships do not require that projects are selected together, but rather define that there could be added benefits to a particular selection of projects. The last relationship defines a constraint on the model where both projects must be selected together, otherwise the project depending on another cannot be included in the portfolio.

To use the data in SPARC, a dependency strength and synergy had to be determined. The strength and synergy were assigned as described in Table 1. As synergies cannot be applied without including a dependency strength, a weak strength was used to indicate the lowest level of dependency – a single relationship. Multiple synergistic relationships indicate a higher level of dependence between projects and a medium strength is therefore assigned. If any project indicated a “Cannot succeed” relationship with a secondary project, then the strength would be assigned as strong, regardless of the number of synergistic relationships. As the collected data did not include any information on synergy for each of the synergistic relationships, an assumption was required to determine a synergy multiplier to perform this analysis.

If there was no indicated synergistic relationship, then the dependency was assigned a default synergy multiplier of 1. As the data included four types of synergistic relationship, each type was given a multiplier value of 0.25 when identified for a secondary project, to be added to be base multiplier of 1. Therefore, the maximum possible synergy to be applied to a dependency would be 2, if all four types of synergistic relationships were indicated for a secondary project. A summary of how the SPARC dependency strength and synergy were determined can be found in Table 1.

Table 1: Criteria used to determine dependency strength and synergy in SPARC.

Dependency strength	“Cannot succeed” = Strong More than 1 synergistic relationship = Medium 1 synergistic relationship = Weak
Synergy	Default value is 1. 0.25 is added for each identified synergistic relationship.

For the resource constraint in the knapsack model, the total costs as submitted by each project were used even though submissions varied on whether inflation was included. This simplified the model to allow for a preliminary analysis to determine the impact of using project dependencies in portfolio optimization. The cost constraint could be improved in future analyses by distributing the costs over time for each project and including inflation for all projects. The budget limit for the portfolio was chosen to be approximately half of the total demand of all the projects, to facilitate the analysis in the absence of an accurate budget limit.

The value of each project was determined through the evaluation of questionnaire responses by subject matter experts in CFD. Each project is evaluated in three categories related to the value it provides upon completion, as documented in [7]. Risk is also accounted for in the project value as a multiplier on the resulting total score from the three value categories. This process provides a single value for each project which is required by the knapsack model.

4.0 RESULTS

After processing the data from 215 projects, a total of 380 dependencies were identified between 132 of the projects. There were 83 projects that did not have any dependencies. A summary of the dependencies can be found in Table 2.

Table 2: Summary of the number of dependencies between 215 major capital projects.

	0 synergistic relationships	1 synergistic relationship	>1 synergistic relationship
Dependent relationships	36	0	3
No dependent relationships	83 (projects)	336	5

To support the examination of relationships between projects, SPARC has a network graph visualization. This graph can be modified to display the different categorical information included in the dataset; it also allows users to zoom in or focus on dependencies for a singular project. Figure 2 shows the full network graph for all the dependencies between the projects used for this analysis. From this overview, a large main cluster of projects is evident. Several smaller clusters are also formed. In addition, it can be seen that many of the projects are connected through weak dependencies. By using this network graph, analysts and decision makers can review and validate the dependencies. They are also able to view higher order dependencies more easily, where the dependencies begin to link together to create more complex bundles of investments.

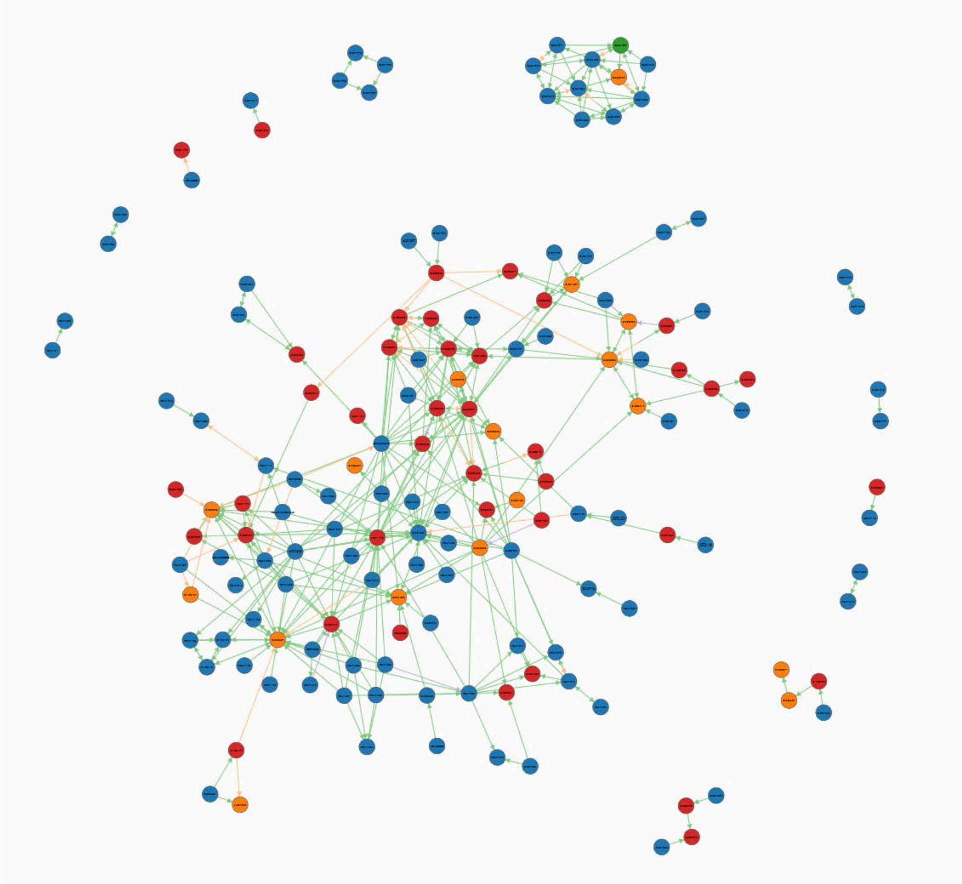

Figure 2: SPARC network graph of all dependencies between capital investment projects. Each node represents a project. The node colour indicates project phase: Identification is Blue, Options Analysis is Red, Definition is Orange, and Green is Unknown. Dependencies are represented by arrows from the primary project pointing to the secondary project. Dependency strength is indicated by arrow colour: Strong is Orange, Medium is Purple, and Weak is Green. Projects with no dependencies are not displayed.

Utilizing SPARC's design for forming or breaking dependencies, Figure 3 shows the network that results when all weak dependencies are removed. This significantly reduces the number of projects that are included in the network and in the clusters. An analyst or decision maker may review this data and determine that many projects seem to indicate synergies with others, decide some of these relationships may be too tenuous to consider in the portfolio optimization model, and only relationships with strengths of medium and strong might be considered. This demonstrates the flexibility of SPARC, where multiple portfolio results may be generated, reviewed, and compared to view the effects of using these different dependency strength considerations. In addition, a significant difference in the number of weak dependencies and medium-strong dependencies can provide further incentive for analysts or decision makers to validate the relationships. This would determine if projects were accurately capturing their relationship data or attempting to inflate their project's relevance to the portfolio by adding synergistic relationships.

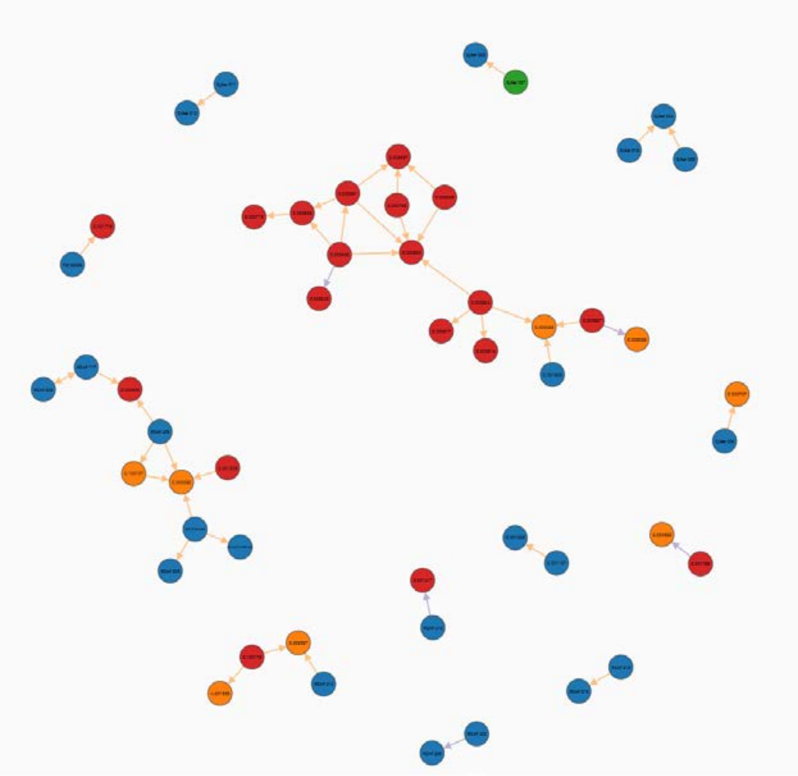

Figure 3: SPARC network graph of the medium and strong dependencies between capital investment projects. Each node represents a project. The node colour indicates project phase: Identification is Blue, Options Analysis is Red, Definition is Orange, and Green is Unknown. Dependencies are represented by arrows from the primary project pointing to the secondary project. Dependency strength is indicated by arrow colour: Strong is Orange, Medium is Purple, Weak is Green. Projects with no dependencies are not displayed.

After reviewing the dependency networks, the analyst or decision maker can move on to generating the optimized portfolios. Table 3 presents the portfolio results from using all four options for dependency strengths: none, strong only, medium and strong, and all three. These results show that as more dependencies are included in the portfolio, fewer projects are selected in the optimal result. This is expected as when more dependencies are included, larger bundles of projects are created. It then becomes more difficult to include these larger sets into the portfolio solution. This is evident in the portfolio with all dependencies, as the large set of weak dependencies in this use case creates more and larger clusters of projects.

Table 3: Summary of portfolio optimization results using different dependency strengths. The Relative Total Value and Relative Total Cost are calculated in comparison to the portfolio results based on no dependencies.

	Portfolio Results			
	No Dependencies	Strong Dependencies	Medium & Strong Dependencies	All Dependencies
Number of Projects Selected	199	195	192	134
Relative Total Value (%)	-	-4.37	-2.59	-23.2
Relative Total Cost (%)	-	0.003	-19.5	-0.373

When comparing the relative total values, the value of the portfolio including all dependencies is significantly lower than the others, by 23%. This suggests that this portfolio may be over-dependent where there are too many relationships being considered creating larger, less valuable project sets, or bundles, that must be included together. In addition, the synergistic effects on this portfolio are not able to compensate for the reduced value. The other portfolios with dependencies perform significantly better with reductions in value of only 2.6 % and 4.4 % compared to the portfolio with no dependencies. As synergies were applied to the values of projects with dependencies, these relative total value results will change with more accurate synergistic relationship information.

The difference in costs between the portfolios is more significant as this initial analysis shows that there can be an approximately 20% reduction in cost with only a 2.6% reduction in value when considering the portfolio with medium and strong dependencies. This shows that including dependencies can result in an attractive alternative portfolio for decision makers, where there is a small trade-off of total value for a significant reduction in total cost. While this is an initial analysis, it demonstrates that exploring project relationships could be beneficial for the management of portfolios of defence projects.

5.0 CONCLUSION

This preliminary analysis has demonstrated that modelling the relationships between major capital defence projects and using values for the strengths of these relationships in a portfolio optimization calculation can give decision makers useful alternatives for consideration. The Australian Department of Defence [18] and DRDC staff supporting the Canadian Army [19] have considered different frameworks for identifying the dependencies between projects. Future research for CFD will certainly consider these frameworks and others for defining interdependency relationships between major capital projects. Future work will also include investigating the use of Natural Language Processing (NLP) to aid in the searching of large volumes of project documentation to find relationship information, as was proposed in [4] and is investigated in [20].

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