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ASOC-3691; No. of Pages 13
ARTICLE IN PRESS
Applied Soft Computing xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Scenario-based multi-period program optimization for capability-based planning using evolutionary algorithms

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ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 26 February 2016
Accepted 1 July 2016
Available online xxx

Keywords:
Capability-based planning
Program optimization
Project portfolio optimization
Multi-objective evolutionary optimization

ABSTRACT

Capability-based planning (CBP) is a strategy focused planning framework that facilitates organizations to systematically develop capacity to achieve their business objectives in highly uncertain, dynamic and competitive environments. Capability programming is an integral part of CBP which requires selecting a portfolio of capability projects for execution, referred as a capability program, such that the overall strategic risk facing the planning organization across a number of projected future operating scenarios is minimized while maintaining the most economical choice. It is a challenging optimization problem that requires handling a number of dynamic constraints and objectives that vary throughout the entire planning horizon. An optimizing simulation approach is presented in this paper that combines an evolutionary multi-objective optimization algorithm with a reinforcement learning technique to generate capability programs which optimize strategic risks and program costs across multiple planning scenarios as well as over a rolling planning horizon. The role of the optimization algorithm in this approach is to search for the non-dominated capability programs at each decision point by minimizing the strategic risks associated with individual capability projects across a number of planning scenarios as well as the total cost of the program. The reinforcement learning algorithm, on the other hand, searches horizontally within the set of non-dominated programs to minimize capability risks and costs over the entire planning horizon. The methodology is evaluated on a test problem generated based on the data distributions in an Australian Defence Capability Plan and the performance is compared with two myopic heuristic methods.

1. Introduction

Capability-based planning (CBP) is a relatively new paradigm that provides an analytical framework for strategic or long range planning using the concept of capabilities. A capability is commonly defined as *the power or ability to do something* [39]. Although the concept of capability has various applications in diverse domains including management science, social science and engineering domains, the origins of CBP are often traced back to defence [15]. In defence jargon, capability refers to *the capacity or ability to achieve an operational effect* [16] and CBP process is defined as *an overarching framework for planning under uncertainty to provide capabilities suitable for a wide range of modern-day challenges and circumstances while working within an economic framework that necessitates choice* [15]. Currently several defence forces around the globe, including the USA, UK, Canadian and Australian Defence Force, are using CBP with some variations in the development of future force structures which can operate effectively in a diverse range of future scenarios [22].

Program management, and in specific project portfolio selection, is a key process in CBP that involves selecting a portfolio of capability projects for programming or execution over the planning horizon. Program management is an emerging area of research in strategic management discipline that aims at bridging the gap between strategy and its implementation in large organizations by focusing on managing a cohort of projects on top of traditional project management. A program is referred to as "a temporary, flexible organization created to coordinate, direct and oversee the implementation of a set of related projects and activities in order to deliver outcomes and benefits related to the organization's strategic objectives" [8]. Program management involves four key processes [33] including identification of all current, proposed and on-hold projects; prioritization or ranking of projects related to their strategic importance; selection of optimal project mix; and progress monitoring. The project portfolio selection, therefore, is

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http://dx.doi.org/10.1016/j.asoc.2016.07.009
1568-4946/

Please cite this article in press as: K. Shafi, et al., Scenario-based multi-period program optimization for capability-based planning using evolutionary algorithms, Appl. Soft Comput. J. (2016), http://dx.doi.org/10.1016/j.asoc.2016.07.009

a key function in program management that involves selecting a subset of desired projects to be programmed or executed that would maximize the fulfillment of the strategic objectives within the available resources. The common considerations in meeting these objectives in portfolio selection problem include budget constraints to account for project costs and the available budget; dependency constraints between the projects, positioning considerations including both the temporal and spatial constraints and threshold constraints ensuring the minimum levels of objectives are fulfilled [34].

Although project portfolio selection problem has seen increasing interest over the last decade [38], the research on this problem in the CBP context is rather scant. Some of the challenges that the CBP process in defence brings to the standard project portfolio selection problem encountered in other industries include very high cost investment decisions (typically 100s of millions of dollars), long time frames for capability development (typically 10s of years) and government imposed hard budget constraints. Among others the two key factors that differentiate defence problems from standard industry problems are the type of optimization objectives and the type of uncertainty associated with these objectives. Business organizations are generally concerned with maximizing profits, revenues, market shares, etc. However in defence the major concern is national security. Subsequently, minimizing strategic risk becomes the number one priority in defence portfolio optimization problems. However, unlike business organizations, strategic risk in defence is often associated with deep uncertainty which comes through a number of factors not relevant to general business problems such as changes in government and political landscapes, national security policies and priorities, and local and global threat scenarios. Dealing with this deep uncertainty requires use of different methodologies than the standard probabilistic risk measuring methods. Scenario-based approaches are usually used to plan under such circumstances [7,46]. This in turn requires portfolios to be selected such that multiple conflicting objectives, e.g. minimization of strategic risks and cost and maximization of balance of investment, are traded off across a number of future scenarios. The process is often continuous since the planning landscape characterized by political, economic, social and technological dimensions change continuously. New capability projects are added regularly to the desired list and existing projects are removed from the plan due to emerging needs under changing strategic environment and political guidance. This requires that the capability program be optimized dynamically over the whole planning horizon.

The work presented in this paper is specifically motivated by the project programming problem in the defence capability planning context, in particular the program management in Australian Defence Force's (ADF) capability development process. The Defence Capability Plan (DCP) [1] outlines ADF's long-term capital program which aims at achieving the long-term strategic goals set out in the Defence White Paper (DWP). Both these documents continuously evolve to address the dynamic nature of Australia's strategic risk environment. Generally, the DWP is revised every four years. The current DWP [2] aims at making the ADF a balanced force capable of meeting every contingency in the next two decades. Various changes can trigger the DCP update process including changes made to Defence portfolio in the budget, emergence of an acute capability requirement and delays in the project schedules. The DCP is generally updated annually and contains major equipment project proposals covering a range of Defence capabilities to be evaluated by the Government over the next decade. The current DCP 2012 (public version) contains 111 projects worth $153 billion [1].

Defence capability planning is a high-stake complex iterative process which requires satisfying several competing objectives under the given constraints. A DCP needs to deliver nation's strategic goals set out in the DWP but within strict financial constraints. Other constraints include delivery schedules, the capacity of Defence and industry to deliver capability, interdependency between projects, and changing political landscapes. Fig. 1 depicts the different factors and drivers considered in the formation of a DCP. Defence often has to prioritize by evaluating capabilities across several future strategic scenarios and weighing each capability on different measures of effectiveness, utility and performance. These complexities make the development of DCP an interesting optimization problem. Furthermore, the combinatorics involved in evaluating the feasibility and relative costs and benefits of a large number of DCP options necessitates the use of computational tools.

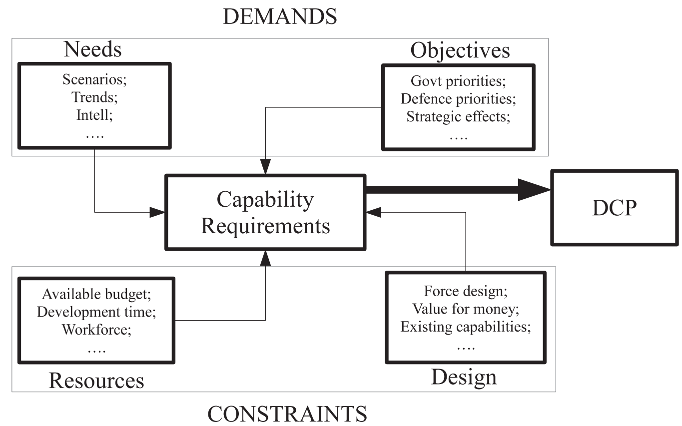

Fig. 1. Defence capability planning.

Current DCP program management practice involves ranking all capability proposals in the Defence portfolio based on a collated score assigned to each capability by Capability Managers (CMs) and Subject Matter Experts (SMEs) across a range of strategic scenarios and then selecting the set of capabilities from the top of the list that could feasibly be programmed within the given budget constraints. Over-programming has been a common practice in previous DCPs, in order to hedge against possible project failure risks.

One limitation of this linear approach is that the decision makers do not get to see many program options to choose from and hence feel pressure to score the individual capability proposals cautiously. In addition there is no transparent mechanism available to analyze multi-dimensional risks associated with different programming options.

This paper presents a methodology for DCP program optimization under periodically changing multiple planning scenarios. The primary aim of the methodology is to search capability portfolios that lie on the efficient frontier, when traded off on a number of objectives including the cost and effectiveness scores in different planning scenarios, not only at a single time period but over the whole planning horizon. To achieve this outcome an evolutionary multi-objective optimization (EMO) approach is first used to model a single period DCP programming problem. The goal of EMO is to generate sets of non-dominated portfolios when measured against cost and effectiveness criteria across multiple planning scenarios at every time period. Evolutionary multi-objective optimization algorithms (MOEAs) are population based techniques that use Darwinian evolution principles, such as natural selection and reproduction, to search the solution space. In effect, they solve optimization problems using multi-point parallel search of the solution space and therefore are considered less susceptible to local optima. In addition, they evolve a set of non-dominated solutions taking into account multiple conflicting objectives. From the DCP programming perspective this means providing the decision makers