OPERATIONS RESEARCH AS A DECISION SUPPORT TOOL FOR ROYAL CANADIAN NAVY FLEET SUPPORT

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INTRODUCTION

Operations research (OR) is not well understood in Canada's Department of National Defence (DND) but offers great potential to address the complexity of the business. Originating from the analysis of wartime operations in the 20th century, it spread from military operations and was adopted by business and industry as a result of the value it brings to the decision-making process. Using mathematical modelling to support strategic-, operational-, and tactical-level decisions, executives, military officers, and government officials have taken advantage of this capability for decades to the benefit of their organizations. Indeed, DND has an integral OR capability that has supported decisions across a broad spectrum of operations, and in particular the Royal Canadian Navy (RCN) has employed it over the years, supporting long term fleet planning, earthquake preparedness, arctic sea power, analysis of the strategic operating environment, underwater acoustic sensor employment, maritime traffic modelling, and others.[1] OR within the RCN and DND, however, is seldom applied below the strategic level, and the capability is centrally controlled at National Defence Headquarters (NDHQ) in Ottawa. Engaging OR resources on difficult problems requires a high-level executive authorization. Limited resources necessitate prioritization, making it very difficult for non-strategic level decisions to access the OR capability. There are, however, many problems at the operational and tactical levels that would benefit greatly from the

[1] Van Fong (Centre for Operational Research, Defence Research and Development Canada), email message to Andrew Sargeant, April 11, 2019.

application of OR. Small improvements at the tactical level can have large strategic effects.

The focus of this paper is on the potential for OR to improve the running of DND's day-to-day business, and not on warfare operations. This paper uses examples from the RCN's Fleet Maintenance Facilities (FMFs) to reiterate the value proposition of OR as a DND capability. The RCN has two FMFs, one in Halifax, NS, and the other in Esquimalt, BC. They execute a broad set of naval support functions for the RCN's East and West Coast Fleets. The naval support functions they undertake are complex, with many variables and unknowns, and the decision making relies to a great degree on the expertise and experience of the people who work there, and the best practices and rules of thumb developed over many years. Rigorous quantitative analysis is not part of the business culture at the FMFs, and mathematical modelling all but unknown. The high complexity of the problems, however, create an environment with great potential for mathematical modelling to contribute to decision support. The conclusions of this paper are not limited to naval support and the examples demonstrate principles that can be applied across the spectrum of DND functions.

To articulate the value proposition of OR this paper begins by reviewing the origins of OR, with specific historical examples that demonstrate the capability. Following this, three complex problem cases FMF business are explored to demonstrate the potential of OR to the RCN today. Considerations on the creation of a more robust OR capability for the RCN are then discussed, along with challenges and limitations, followed by concluding thoughts.

OR ORIGINS

At its roots OR is a response to the demand for quantitative analysis to support hard decisions. Most agree that OR was born in the 1930s as the field of applied mathematics, hitherto a tool primarily used in physics and engineering, was engaged to confront the increasing complexity of decision making resulting from rapid advances in technology during that period. One such rapid advance in technology was the development of radar prior to and during World War II, which forced OR to come of age and be recognized as a valuable tool to gain advantage over the adversary.[2] The importance of radar during World War II is hard to overstate. Decisions concerning the operation and use of this advanced technology were challenged by the system's technical complexity as well as the multitude of operational factors affecting its employment. Further complicating matters (and adding to the urgency of the situation) was the adversary's use of the same technology. By applying the scientific method to the radar problem, and by *researching* the *operation* of the entire air warning system, better decisions were made, and *operations research* became a distinct capability within the Royal Air Force.[3]

The introduction of radar drove pronounced changes in the performance of many warfare procedures and, although offering significant capability gains, created a whole set of new problems. Leading up to the war Britain's early warning system was a collection of ground observers, continual air patrols, observation balloons, and air defence batteries on persistent alert, with no capability to provide intercepting pilots with value-added

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[2] Operational Research Society, *OR, Defence and Security*, ed. Roger A. Forder (Basingstoke, UK: Palgrave Macmillan, 2015): 1.
[3] Joseph F. McCloskey, "The Beginnings of Operations Research: 1934-1941," *Operations Research* 35, no. 1 (1987a): 147.

information when they scrambled. As radar was integrated to this system, experiments were conducted to understand how the operation of the overall system worked, including the communication between layers of the early warning system, the performance of the radar operators, and the integration of each of the elements. This, when combined with the results of a detailed analysis of every failure to intercept raids, led to changes that obviated the requirement for persistent fighter patrols and air defence high alert status, and provided much improved intercept information for use in fighter direction and control.[4]

Analytical methods were also applied to the use of radar in the search and targeting of German U-boats, which yielded detailed procedures for aircraft to find U-boats without giving themselves away, the search patterns to be used depending on the situation (day or night, U-boat submerged or on the surface, etc.), and settings for air-dropped depth charges that drastically increased their effectiveness.[5] Another radar example comes from the later years of the war in the Pacific and involves an analysis of suicide bomber interception that found the weak link to be significant inaccuracies in the shipborne height-finding radar. The analysis determined that poor maintenance, training, and calibration tests were the cause of the inaccuracies, and stringent procedures were ordered across to the fleet to reduce them.[6]

Statistical methods play a critical role in OR. One famous example known as the "German Tank Problem" involved the estimation of tank production in Germany. Ruggles

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[4] Great Britain Air Ministry, *The Origins and Development of Operational Research in the Royal Air Force*, Vol. 3368 (London, UK: H. M. Stationery Office, 1963): 10-32.
[5] Joseph F. McCloskey, "British Operational Research in World War II," *Operations Research* 35, no. 3 (1987b): 456.
[6] Philip McCord Morse and George E. Kimball, *Methods of Operations Research*, 1st rev. ed. (Alexandria, Va: Military Operations Research Society, 1998): 56.

and Brody describe the problem in detail in their 1948 paper,[7] a summary of which follows here. The challenge for Allied Intelligence in estimating enemy force size was hampered by German propaganda and inaccurate reports from ex-POWs, and methods for making more reasonable estimates were sought. As the war progressed, post-battle assessments were conducted and information on the serial numbers of German tanks was collected, which eventually led to the discovery that the tanks were numbered sequentially. If a series is known to be $\{1, 2, 3, \ldots, x\}$ and only a few of the actual members of the total population are known (in this case, the collected serial numbers), the total population x can be estimated using basic techniques like the *Minimum Variance Unbiased Estimator*.[8] Estimations like this allowed the Allies to make more accurate assessments of German war manufacturing and even forecast the decline of German industrial output despite reports to the contrary.

A Naval application of OR in World War II involves the study of convoy operations and is summarised here.[9] Convoys occurred frequently enough to have good data about their operations. Statistical analysis showed that convoys with more escorts suffered fewer sinkings. Shipyards were already working at capacity and unable to produce more escorts, so an increase in production was an impractical solution. This led to further statistical analysis and the discovery that smaller convoys suffered more sinkings than larger convoys, which was contrary to the conventional wisdom of the time, and the decision was made to increase the size of the convoys, resulting in fewer sinkings

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[7] Henry Brodie and Richard Ruggles, "An Empirical Approach to Economic Intelligence in World War II," *Journal of the American Statistical Association* 42 (1947), 72-91.
[8] "The German Tank Problem," last modified November 14, accessed March 24, 2019, https://www.statisticshowto.datasciencecentral.com/german-tank-problem/. Minimum Variance Unbiased Estimator: Total population = highest known number – (highest known number / sample size) – 1
[9] Bernard Lovell, "Blackett in War and Peace," *The Journal of the Operational Research Society* 39, no. 3 (1988): 225.

overall. This is an example of quantitative analysis contributing to executive decision-making, especially in light of previously held assumptions.

Many examples exist of OR being applied across the spectrum of military operations during World War II. In most, the mathematical techniques applied were quite simple and implemented with meagre resources, but the potential to improve capability was clear. The focus of the problem-solving effort was on the study of how the components of a system operate in concert, identifying the factors affecting the outcomes, and using the results to inform decision making. The lack of fast computing also limited the researchers: as computing speeds increased in the latter half of the twentieth century and data management became more robust and automated, applied mathematicians were able to use more advanced techniques and develop larger models to represent more complex situations. As computing speeds increased so also did the accessibility of computing resources, and OR started to be applied not just in the military, but in industry, business, and government. Warfare offers many tactical scenarios that can benefit from OR, but as OR broadened its sphere of influence after World War II, it became more involved in optimizing business processes and decision-making at the corporate and institutional levels.

The independent ability to collect and manipulate data also heralded the onset of analytics,[10] which is now ubiquitous in the business world, and a growing capability in the defence arena. Analytics focuses more on cross-organization fact-based decision making, as opposed to targeted problem solving, which is more the domain of OR.[11] The

[10] Matthew J. Liberatore and Wenhong Luo, "The Analytics Movement: Implications for Operations Research," *Interfaces* 40, no. 4 (July, 2010): 315. doi:10.1287/inte.1100.0502.
[11] *Ibid*., 319.

lines are blurred, however, and as analytics advanced the techniques of both offered lessons for analysts, operations researchers, and decision-makers alike. Certainly, with the energy and resources currently applied to analytics within DND, OR has taken somewhat of a backseat. This growing capability in analytics, however, offers new opportunities for OR to become an even more powerful decision-making tool. The culture is changing to include more quantitative analysis in decision making, and data management is improving. The next section explores three complex problem cases experienced by the FMFs in which OR, supported by analytics, can support the hard decisions.

OR OPPORTUNITIES

The activities involved in naval fleet support offer an almost unlimited set of opportunities for OR to inform decision making. In modern navies, engineering, maintenance, and supply chain operations have become extremely complex, the decision making non-trivial, and the idea of what represents "good performance" difficult to define. The problems associated with these operations are often "hard" problems, in that they have many variables, many unknowns, may possible solutions of varying value, are often subject to human behaviour (which is difficult to predict), and the search for optimal solutions may approach infinity in terms of time to solve. The problems are difficult because warships are very advanced systems of systems with complicated supply chains and sophisticated engineering and maintenance requirements. They have many stakeholders, including operators, maintainers, engineers, logisticians, planners, project managers, military personnel, public service employees, and defence industry. The operational demands on warships often exceed their supportability: the time, material, and expertise to conduct support operations are rarely optimal and often entirely lacking in terms of the demands. What follows is a selection of naval fleet support problems that exist today, and to which the application of OR would provide tangible benefits with only a modest resource investment.

Maintenance Planning

Canadian frigates in their operational cycle (i.e., not in refit) are supposed to undergo 12 weeks of dedicated second line maintenance[12] per year, normally allocated as three Short Work Periods (SWPs) of four weeks in duration. The purpose of these maintenance windows primarily the execution of planned maintenance activities, but they also allow for urgent corrective maintenance to be carried out in support of upcoming missions. Depending on the operational schedule and the maintenance demand the 12 weeks may be slightly reduced or increased in an effort to find the optimal operations-maintenance balance. As a rule, however, the maintenance demand exceeds the time allotted to do it. Decisions that maintenance planners deal with on a continual basis are centred on the question of which maintenance should be done in the time-constrained windows? From this question, several more are spawned: what maintenance will best support the ship's next mission? What maintenance will best prevent failures that may impact future missions? How to allocate limited maintenance resources across competing platforms? These types of questions have traditionally been managed using best practices and rules of thumb developed over decades of conducting naval maintenance.

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[12] Second line maintenance activities are those normally conducted at one of the FMFs due to their technical, material, expertise, or time demands. First line maintenance is most often conducted by ship's staff, and third line maintenance is most often conducted by the manufacturer, often at its facility.

Problems of this type are known as *selective maintenance* problems.[13] A simple representation of the problem involves one ship, comprised of multiple systems. The ship carries out a series of missions with breaks for maintenance between missions. Maintenance is carried out on the systems to increase the probability of successfully completing the next mission. Each possible maintenance activity has a different impact, or value, on the next mission success. The total maintenance demand exceeds one or more of the available resource capacities, normally time, cost, human resources, or material. The question then becomes: of the total set of maintenance activities required by the ship, what subset of maintenance activities should be undertaken to maximize the probability of successfully completing the next mission? Several models have been created to assist with the problem[14]. Cassady, Pohl, and Murdock proposed a mathematical modelling framework to assist in the determination of which maintenance actions should be selected.[15] Khatab et al developed a nonlinear stochastic optimization model for multi-component systems that determines a subset of maintenance activities, optimized for cost, and given a constrained time window and the system reliability required to complete the upcoming mission.[16] The problem becomes more complicated as more real-life factors are incorporated into models. Liu and Huang use a genetic algorithm to incorporate the

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[13] Rajanand Rajagopalan and C. Richard Cassady, "An Improved Selective Maintenance Solution Approach," *Journal of Quality in Maintenance Engineering* 12, no. 2 (2006): 173.
[14] For a description of the mathematical modelling techniques described herein, see Frederick S. Hillier and Gerald J. Lieberman, *Introduction to Operations Research*, 10th ed. (New York, NY: McGraw-Hill Education, 2015).
[15] C. Richard Cassady, Edward A. Pohl and W. Paul Murdock, "Selective Maintenance Modeling for Industrial Systems," *Journal of Quality in Maintenance Engineering* 7, no. 2 (2001), 104-117.
[16] Abdelhakim Khatab et al., "Selective Maintenance Optimisation for Series-Parallel Systems Alternating Missions and Scheduled Breaks with Stochastic Durations," *International Journal of Production Research* 55, no. 10 (2017), 3008-3024.

concept of imperfect maintenance into their model, which accounts for the fact that maintenance actions are completed to varying degrees of quality.[17]

These types of maintenance planning decisions occur on a regular basis at the FMFs. SWPs are generally planned by prioritizing required maintenance activities on an individual ship basis and creating a maintenance schedule for each ship. Project managers then must negotiate with the managers of other ships, workshop leaders, and RCN operations personnel to create a workable schedule based on actual resources available. Although the SAP-based Defence Resource Management Information System (DRMIS) is used to manage jobs, shop loading, and schedules, no attempt at optimization is made. Furthermore, because every SWP project manager is focused on completing his or her SWP, there is little thought put to the optimization of fleet maintenance as a whole beyond inquiring with senior management on unreconciled resource conflicts. Applying optimization methods to this, the RCN’s own version of the selective maintenance problem, help ensure the right maintenance is conducted and assist in the scheduling or fleet-wide resources.

Maintenance Scheduling

SWP schedules are created in DRMIS using a bolt-on software called GWOS (Graphical Work Order Scheduler), an SAP-licensed third-party product that provides graphical project management functionality similar to Primavera or Microsoft Project. The software interacts well with DRMIS to create maintenance schedules by automatically updating existing work orders in DRMIS as changes are made, level-

[17] Yu Liu and Hong-Zhong Huang, "Optimal Selective Maintenance Strategy for Multi-State Systems Under Imperfect Maintenance," *IEEE Transactions on Reliability* 59, no. 2 (2010), 356-367.

loading amongst available resources, and other basic scheduling functionality. The software offers no optimization capability, however (indeed even the most advanced project management tools like Primavera have only limited optimization capability), which means that any attempt at optimization is carried out by the schedulers and project managers and is largely based on best practices and rules of thumb developed over many years. There is no computer-assisted ability to plan and sequence jobs in SWP to maximize for schedule, cost, or scope, and no ability to understand if a project or job will finish on time or not, and why. These are critical questions in most projects, but particularly pressing in SWPs. The end of an SWP is a hard stop: the ship will leave for its next planned mission on its planned date, barring any mission-critical unrepaired corrective maintenance. Due to the vast number of variables involved with maintenance planning and execution (supply chain issues, project planning issues, human resource management issues, external factors, etc.), it is very difficult to give reliable status reports to leadership. DRMIS, however, has been collecting data on maintenance activities since 2003, so there are millions of data points ready for analysis, if only the analytical resources were applied.

In 2017 the FMFs partnered with the Centre for Operational Research (CORA), a division of Defence Research and Development Canada (DRDC), to look at the scheduling problem.[18] In a short amount of time with only one DRDC scientist working on the problem, key insights were uncovered that challenged long-held assumptions about maintenance scheduling and laid the foundation for significant improvements in SWP scheduling. DRDC approached the problem using a variety of advanced statistical

[18] The FMFs have no integral OR capability of its own and therefore had to partner with DRDC CORA.

modelling techniques, including Gaussian mixture modelling, K-mean clustering, regression trees, random forests, hidden Markov modelling, and others[19].

One of the key assumptions about maintenance scheduling at the FMFs is that the supply chain is largely to blame for jobs not being finished on time, i.e., parts don't arrive on time (for a long list of possible reasons). DRDC's regression tree analysis of the FMF maintenance data set suggests that this is not actually the case, and that most of the schedule variance of individual jobs is due to the workshop doing performing the maintenance activity.[20] Based on the statistical knowledge of what causes jobs to not complete on time, DRDC then built a predictive model that determines the likelihood of a job not finishing on time.

These models, created in a relatively short amount of time with limited resources, completely changed the discussion around scheduling at the FMFs. The fact that workshops at then FMFs account for so much of the scheduling issues started a conversation about why that is. This particular DRDC project didn't have the scope to investigate further, but if the FMFs had a dedicated OR team, that would be a logical next step. Understanding more about why jobs don't finish on time will allow project managers, workshop managers, supply managers, and others involved with maintenance planning and execution to make early changes that reduce overall schedule risk. In SWPs, schedule is king, and a lot of work needs to be executed in a very short amount of time. OR can help the FMFs in this respect to support the fleet getting back to sea on time.

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[19] For more on the statistical modelling techniques described herein, see Trevor Hastie, Robert Tibshirani, and Jerome Friedman, *The Elements of Statistical Learning: Data mining, inference, and prediction*, 2nd ed. (New York, NY: Springer, 2016).
[20] David Maybury, *Predictive Analytics for the Royal Canadian Navy Fleet Maintenance Facilities* (Ottawa, ON: Defence Research and Development Canada, 2017): 13-16.

FMF Supply Chain

The combination of advanced technologies and globalization leads to complex supply chains, and this is certainly the case for supply chains that provide material for naval maintenance. The wide array of systems onboard Canadian warships are spread across several domains, including mechanical, electrical, electronic, and structural, to name a few, and the material is sourced from all over the world. The design and management of naval supply chains are sometimes carried out by public service employees, sometimes contracted to industry, and other times a combination of both. DND, however, does little to optimize the operation of its supply chains, beyond relying on the experience and expertise of the military and public service personnel who work in the field. Furthermore, DND supply chains are subject to significant pressures linked to Canadian procurement policy, which is often at odds with delivering naval capability efficiently and creates tension, competing objectives, and constraints on finding optimal solutions.

Supply chain problems are widely studied, however, in both academia and industry. One of the largest chemical companies in the world, BASF, used OR to support strategic and operational decision making, and also to tackle several tactical supply chain problems, including a custom inventory model for their unique chemical production processes, a sophisticated predictive model for demand forecasting in the process industry, and quantitative decision support for integrating the production and marketing departments to increase value.[21] Closer to the defence realm, the United States Coast Guard used OR to improve its supply chain in four projects: it used linear programming

[21] Robert Blackburn, Josef Kallrath and Steffen T. Klosterhalfen, "Operations Research in BASF's Supply Chain Operations," *International Transactions in Operational Research* 22, no. 3 (2015): 386-399.

models to (1) link disparate parts databases in order to improve inventory management, (2) assist in repair decisions concerning the use of in-house or contracted resources, (3) assist in a helicopter upgrade project that minimized aircraft downtime and forecasted future parts needs, and a simulation model to (4) better understand resource bottlenecks in helicopter overhaul projects and recommend efficiencies.[22] And in the forestry industry, a review of OR methods used to assist in forestry industry supply chain planning and management found frequent use of heuristics, meta-heuristics, network models, mixed integer programming, and stochastic programming methods[23] across a broad range of strategic, operational, and tactical problems.[24]

One of the primary questions concerning project managers at the FMFs is: will the material arrive on time to support the planned jobs in accordance with the schedule. DRMIS is a transactional database tool and therefore has little ability to perform analysis functions. In other words, despite the fact that DRMIS tracks inventory, the vast amount of inventory data is not used in support of complex decision making. The ground truth on parts availability and delivery is still obtained by phone calls, emails, and conversations with material managers and suppliers. Furthermore, no decision support tools or attempts at optimization have been developed to support inventory control and management. This means that if a project manager at an FMF needs to track down a part that is urgently needed, he or she relies on his or her relationships to get the job done. This problem space is ripe for the application of OR. DRMIS has been collecting material data for many years

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[22] Kent Everingham et al., "Operations Research Enhances Supply Chain Management at the US Coast Guard Aircraft Repair and Supply Center," *Interfaces* 38, no. 1 (2008): 64-65.
[23] For more on these techniques, see Frederick S. Hillier and Gerald J. Lieberman, *Introduction to Operations Research*, 10th ed. (New York, NY: McGraw-Hill Education, 2015).
[24] Sophie D'Amours, Mikael Rönnqvist and Andres Weintraub, "Using Operational Research for Supply Chain Planning in the Forest Products Industry," *INFOR* 46, no. 4 (2008): 269-270.

and large data sets are available to train statistical learning models. As just one example, with the right expertise it would be a relatively straightforward exercise to build a prediction tool to determine the probability of a part arriving on time, which could be employed early on in project planning. In an ideal world the project managers would be able to apply the outputs of these models to their risk management practices and obtain reliable information on the impacts of material on their project schedules[25]. This is just the tip of the iceberg in terms of supply chain optimization, an area with immense potential for DND.

This section has provided a review of just three problem sets concerning naval fleet support that exist today at the FMFs and that could be tackled with minimal resource investment or reallocation. Their value lies in the potential to drive the schedule objectives of FMF projects, or in creating efficiencies that save time and energy or drive down cost. An almost unending list of problems sets could also have been discussed, including schedule optimization and deconfliction, critical path analysis, decision support for project scope changes, resource optimization (e.g., jetty cranes shared between ships), facility layout optimization, and many others. All of these are problems are experienced by other industries and, to some degree, are studied in academia, so the groundwork exists to apply OR tools to the complex problems at the FMFs. The next section explores the feasibility of building an integral OR capability to bolster decision-making in naval support.

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[25] At the time of writing the FMFs and DRDC CORA had commenced work in this area, however no documentation was available describing progress or results.

TOWARD AN INTEGRAL OR CAPABILITY

DRDC CORA has a team of defence scientists based in NDHQ who are tasked across the DND Level One (L1) organizations to support complex decision-making with OR. Typically, each L1 has a small team of scientists assigned to them semi-permanently. This framework allows the resources to be pooled and prioritized across DND, while ensuring each L1 has some degree of reliability and constancy in terms of dedicated OR capability. The OR team normally works quite closely with the L1, who generally establishes priorities is most often focused on supporting strategic decision making. Resources being quite limited, operational and tactical problems often have a lower priority in comparison to strategic problems. OR to support strategic decision making is valuable to an institution, however OR at the operational and tactical levels also can be of great benefit: small tactical improvements can have large strategic effects. The challenge is in communicating the benefit of applying OR resources at the operational and tactical level.

The FMFs have no in-house OR or decision-support expertise. With the strong push by the RCN to create a robust analytics capability during the last several years, the general awareness of quantitative methods to support decision making has increased, however this has been (and will continue to be) limited because most employees don’t have advanced degrees in mathematics and statistical methods, which are required to address the truly difficult problems that have much higher payoffs. Given the scope and cost of the activities the FMFs undertake, the number of employees spread across diverse skill sets,[26] the advanced technology of the systems being worked on, the reliance on a

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[26] Each FMF employs approximately 1000 people, including 850 public service employees and 150 military personnel.

cumbersome supply chain, the demanding schedule requirements, and the interaction with a wide array of stakeholders (over whom the FMFs often have little influence) there is a great need for an in-house OR capability to support decision making at the operational and tactical levels.

What would an in-house OR capability look like at the FMFs? A small team of three or four defence scientists with backgrounds in operations research would likely create a formidable OR capability. As experts in mathematical modelling, statistical methods, and data science, this OR Team would be tasked to support the hard problems that management is faced with, some of which were described in the previous section. By being embedded in FMF operations the team would learn the intricacies and complexities of the business, which would improve the overall OR effort. As an integral capability, the decision makers would see how OR can help solve hard problems and develop productive relationships with the OR Team that would foster an overall decision-making culture supported by quantitative analysis, and not just best practices and rules of thumb. Opportunities exist to partner with industry as well. Although the core OR capability should continue to reside within DND, contracts could be established to augment capacity with industry expertise as needed.

There are, of course, challenges in setting up a local OR capability. Currently DRDC has a monopoly on the hiring and employment of defence scientists, so an arrangement would have to be made to allow the RCN and the FMFs to create their own dedicated teams, recognizing that these types of human resource changes can take a long time to resolve. Coupled with this is the reality that people with advanced education in mathematics and broad experience in OR are both difficult to find and in high demand. Furthermore, there is no culture of quantitative analysis at the FMFs, so a significant effort early on would involve education and communication between stakeholders. In terms of FMF leadership, applying OR to decision making is a learned skill, and as for the work force, people are generally wary of operations researchers out of fear their jobs will be taken away. A final challenge, and due to DND's information technology framework a not-insignificant one, is concerned with computing infrastructure. Building mathematical models takes dedicated software and hardware above and beyond the normal DND desktop workstation. Introducing new software and hardware would require buy-in from the Assistant Deputy Minister for Information Management, whose resources are similarly stretched across many other DND priorities.

Although OR has proven itself a valuable decision-support tool, it has limitations that should be understood by decision-makers in order to get the most out of it and avoid pitfalls. OR is about applying the scientific method to an operational problem and using quantitative analysis to aid in the solving of it. It is very good at solving tangible problems with measurable inputs and outputs but becomes limited when faced with the less tangible or measurable. For example, many aspects of human behaviour are difficult to quantify, and therefore also difficult to model mathematically. The results of OR thus represent only one piece of the decision-maker's puzzle, and not a prescriptive decision tool. As the *Harvard Business Review* published in 1953 in an article analyzing the advantages and limitations of OR, the role of executive judgement and intuition remains the cornerstone of sound decision making[27]. This conclusion remains true today: the successful executive will combine the results from an OR problem with their own expertise and experience to render a good decision. A further limitation of OR is that it

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[27] C. C. Herrmann and J. F. Magee, "Operations Research for Management," *Harvard Business Review* 2 (1953): 111.

does not happen overnight: it is an analytical process following the scientific method and takes time to do properly. Although a worked-up team with a good knowledge of the business can tackle problems relatively rapidly, significant time may be required to truly understand the problem in question before it can be accurately modelled mathematically. OR is therefore less suited for urgent, one-off problems, and more suited to systemic problems, or those of a repeating nature.

Despite these challenges and limitations, there is clear value in creating a small OR team inside the FMFs. Even a team of one or two operations researchers with the right backgrounds working within the FMF lines of business and using existing computing resources would have a pronounced effect on naval support activities in the dockyards.

CONCLUSION

The principles identified herein are not exclusive to the problem sets discussed in the examples above and can be applied across similar functions in the RCN and DND. Human beings have great difficulty addressing problems with large numbers of variables, competing objectives, and uncertainty: characteristics that describe the nature of many hard problems within DND. The approaches discussed here are extendable to a broad range of DND business management problems, including the problem of force readiness planning (comprising personnel readiness, material or technical readiness, training, and logistics), HR management (understanding personnel trends and impacts on the organization), plant production decisions (layout of FMFs and other production facilities, optimization of plant processes, etc.), project management (critical path analysis, project crashing, optimizing for schedule, cost, or scope, etc.), and many others. As operations researchers learn more about DND business and decision-makers learn more about the application of OR to their decision making, more problem sets will emerge, offering even more potential for improvement of the business, and the overall process will become a streamlined, valuable, integral capability.

This requires a concerted effort, however. In the example of the FMFs, the Commanding Officers need to make this a priority and assign the resources for implementation. Leaders and executives with no experience in OR can be reluctant to assign scarce resources before objectively observing the benefit to their business, as was indeed the case for the rollout of the analytics program. The capability of OR should therefore be demonstrated so the value proposition is clear. The cases described in this paper are of a sufficiently limited scope that they would demonstrate this value with only minimal investment.

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