OFFICE OF
THE PARLIAMENTARY BUDGET OFFICER
CANADA
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DIRECTEUR PARLEMENTAIRE DU BUDGET

Budget Analysis for the Acquisition of a Class of Arctic/Offshore Patrol Ships

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The mandate of the Parliamentary Budget Officer (PBO) is to provide independent analysis to Parliament on the state of the nation's finances, the government's estimates and trends in the national economy; and upon request from a committee or parliamentarian, to estimate the financial cost of any proposal for matters over which Parliament has jurisdiction.

PBO received requests from Mr. Jack Harris, Member of Parliament for St. John's East, and Ms. Joyce Murray, Member for Vancouver Quadra, to undertake an analysis of the feasibility of the government's plan to deliver six to eight Arctic/Offshore Patrol Ships (A/OPS) for $2.8 billion by 2024.[1,2,3] This report responds to these requests by providing an independent cost estimate for the acquisition of the ships, as well as a sensitivity analysis to estimate the possible costs due to key project risks.

The cost estimates and observations presented in this report represent a preliminary set of data for discussion and may be subject to change as the project progresses or new data is provided to the PBO. The cost estimates included reflect a point-in-time set of observations based on limited and high-level data obtained from a variety of sources. These high-level cost estimates and observations are not to be viewed as conclusions in relation to the policy merits of the A/OPS project.

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[1] Public Works Government Services Canada (2013a)

[2] National Defence and the Canadian Armed Forces (2014a)

[3] The full A/OPS budget is actually $3.1 billion but it includes $300 million for jetty improvements at Halifax, Esquimalt and Nanisivik leaving only $2.8 billion for the ships themselves. See Canadian American Strategic Review (2007) and Proussalidis (2013)

Contents

Glossary

A/OPS	Arctic/Offshore Patrol Ship
CAF	Canadian Armed Forces
CCG	Canadian Coast Guard
CCGS	Canadian Coast Guard Ship(s)
CPI	Consumer Price Index
CSC	Canadian Surface Combatant
DELMS	Definition, Engineering, Logistics and Management Support
GAO	U.S. Government Accountability Office
HST	Harmonized Sales Tax
IACS	International Association of Classification Societies
JSS	Joint Support Ships
LCS	Littoral Combat Ship
LSL	Louis St. Laurent
NSPS	National Ship Procurement Strategy
OPV	Offshore Patrol Vessel
PBO	Parliamentary Budget Officer
PC	Polar Class
RFP	Request for Proposals
SOR	Statement of Operational Requirements

Executive Summary

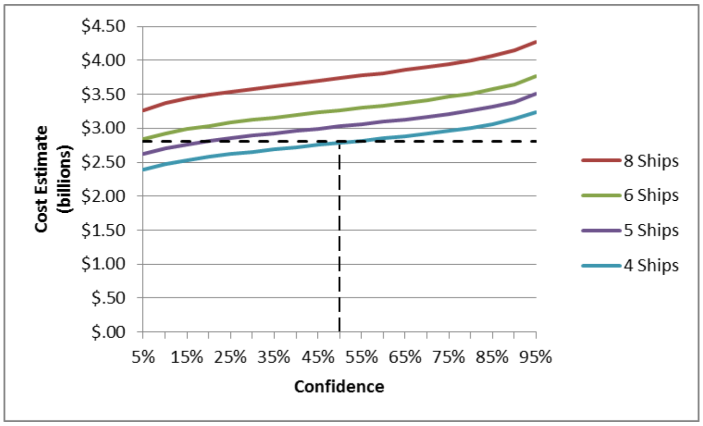
The National Shipbuilding Procurement Strategy (NSPS) was announced by the Government of Canada in June 2010 with the objective of replacing the current surface fleets of the Royal Canadian Navy and the Canadian Coast Guard. One of the ships that is included in NSPS is the Arctic/Offshore Patrol Ship (A/OPS).

The objective of the A/OPS project is to deliver six-to-eight ice-capable, offshore patrol ships for the Royal Canadian Navy, as well as jetty infrastructure.[4] These ships will conduct armed sea-borne surveillance in the Arctic and "support other units of the Canadian Armed Forces (CAF) in the conduct of maritime-related operations and […] support other government departments in carrying out their mandates, as required" (e.g. the Canadian Coast Guard).[5] The budget for the project has been set at $3.1 billion:[6] approximately $2.8 billion to acquire the ships with the remaining $274 million designated for jetty infrastructure improvements at Esquimalt, Halifax, and Nanisivik in Nunavut.[7,8,9]

PBO analysis suggests that the current budget will be insufficient to procure six to eight A/OPS as planned. Rather, it is more likely that, if there are no delays, the current budget will allow for four ships to be built. However, any delay over a year would mean that the budget would likely only be sufficient to build three ships. Schedule slips, therefore, may have a significant impact on the government's purchasing power and on other projects down the pipeline, such as the Canadian Surface Combatant.

Summary Figure 1 below shows the estimated cost for delivering four, five, six, and eight ships at confidence levels between 5% and 95%.[10] As can be gleaned from the figure, only four ships can be delivered with the $2.8 billion budget at the minimum acceptable confidence level of 50%. Alternatively, the government could increase the budget by an estimated $470 million to $3.27 billion to acquire six ships with a 50% confidence interval.

Summary Figure 1 Estimated Ship Cost as a Function of Confidence Level



Source: PBO using TruePlanning software.

Summary Table 1 below presents the estimated delivery dates for each ship. It was assumed that one ship would be delivered each year similar to previous ships of similar size.[11] It is estimated that it will take three years to complete the first ship and 30 months for the second ship. Due to learning curve increases in efficiency, ships 3 through 8 can take less time, or fewer employees, or a combination of both.

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[4] National Defence and the Canadian Armed Forces (2013a)

[5] Ibid.

[6] Public Works Government Services Canada (2013a); See Appendix E for the current A/OPS reported budget and expenditures.

[7] Thomas (2007b)

[8] Canadian American Strategic Review (2007)

[9] Canadian American Strategic Review (2012)

[10] In order to account for project risk, the cost estimators also run a risk analysis to assess how changes to key inputs (e.g. the weight of the ship) might impact the cost estimate. This analysis produces a range of potential cost estimates, which are ordered from lowest to highest. The mid-point of these estimates is called the 50% confidence level and is considered a minimum acceptable standard when selecting a budget. Organizations that are more risk-averse or that undertake more risky projects may budget at the 80% confidence level, where only 20% of estimates yield values greater than the budget.

[11] See Halifax-class frigate Wikipedia (2014c)

Given the estimate that four ships can be built with the current budget, the fourth and final A/OPS would be completed in early 2021.

Summary Table 1 Ship Delivery Dates

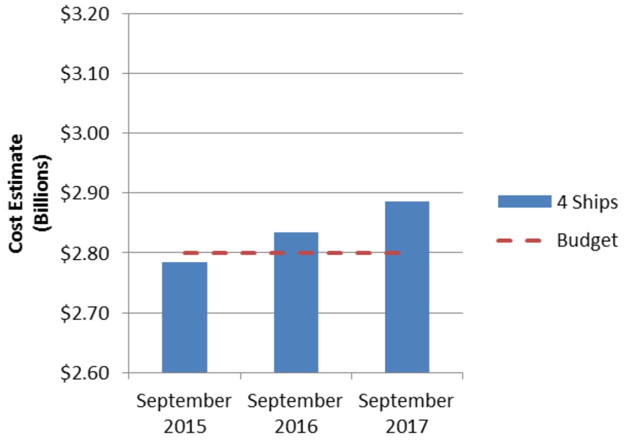
Ship number	Delivery Date
1	Likely in 2018
2	January 2019
3	January 2020
4	January 2021
5	January 2022
6	January 2023
7	January 2024
8	January 2025

Sources: PBO and TruePlanning.

Due to inflation, the effect of delaying the start of construction of the first ship causes the estimated cost to increase to the point where only three ships can be built rather than four.[12] Summary Figure 2 below shows the effect on the cost estimate of a one- and two-year delay with a 50% confidence level. As can be seen from the figure, a one year delay would result in the project being $34 million over budget. A two year delay would result in the project being $85 million over budget. These figures suggest that if there is a delay, one or a combination of three things will happen: the budget will be increased, the number of ships paired back, or the ship's capabilities will be paired down.

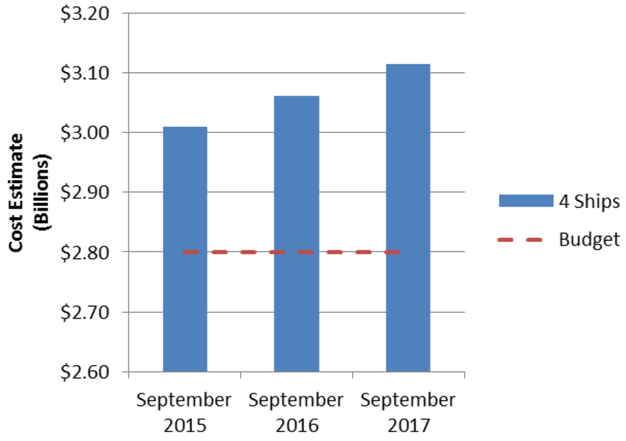
Summary Figure 3 below shows the effects for the same delays in construction start but using an 80% confidence level. With a one-year delay, the cost of four ships is estimated to be $206 million over budget and with a two-year delay it is estimated to be $310 million over budget. Even with no delay, to achieve four ships with 80% confidence is $201 million over budget.

Summary Figure 2 Ship Cost Increase Due to Delay with a 50% Confidence Level



Source: PBO using TruePlanning software.

Summary Figure 3 Ship Cost increase Due to Delay with an 80% Confidence Level



Source: PBO using TruePlanning software.

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[12] Military procurement has a higher rate of inflation than CPI. See Arena, Blickstein, Younossi and Grammich (2006) and Congressional Budget Office (2013).

1 Introduction

The Parliamentary Budget Officer (PBO) may, upon request from a committee or parliamentarian, estimate the financial cost of any proposal over which Parliament has jurisdiction.[13] This report responds to requests to provide an independent budget estimate for the Arctic/Offshore Patrol Ship (A/OPS) project.

The PBO undertook an independent cost estimate of the A/OPS project to determine the reasonableness of the government's plan to deliver six to eight ships for $2.8 billion by 2024.[14]

The baseline estimate assumes a construction start date of September 2015 as well as a build schedule that minimizes total cost. The cost is separated out by each ship so it is possible to determine how many ships can be built within the allotted budget as well as to show how much more money it will take to build additional ships. Further to the baseline scenario, estimates of the cost increases due to delaying construction start by one and two years are calculated. Sensitivity analysis is carried out by varying the ships' weight and complexity.

Consistent with Treasury Board Policy, the A/OPS budget is required to cover all acquisition costs, inclusive of salaries, contributions to employee benefits and pensions, project management, contracts, design fees, licensing fees, industrial and regional benefits management, construction, quality assurance, contingency, and all applicable taxes (HST = 15% in Nova Scotia).

The remainder of this report has three sections. The first section provides background information regarding the A/OPS program and polar class ships in general. The second section describes in detail the selected estimation methodology. The results are outlined in the final section.

2 Background

In July 2007, the Government of Canada "announced a plan to procure six-to- eight armed naval icebreakers" (also known as A/OPS).[15] These ships will conduct armed sea-borne surveillance in the Arctic and "support other units of the Canadian Armed Forces (CAF) in the conduct of maritime-related operations and support other government departments in carrying out their mandates, as required" (e.g. the Canadian Coast Guard).[16]

The budget for the project has been set at $3.1 billion:**[17]** approximately $2.8 billion to acquire the ships with the remaining $274 million designated for jetty infrastructure improvements at Esquimalt, Halifax, and Nanisivik in Nunavut.[18,19,20]

The original plan for Nanisivik was to create a naval station which would operate year round.[21] This was subsequently changed to a refuelling stop that would be manned by "crews flown up from the south as needed."[22] Notwithstanding that the original budget for the full naval station was $100 million and that the simple fuel station now has an increased budget of $146 million, it is assumed that the overall jetty infrastructure budget for all three ports remains the same (i.e. $274 million).[23]

While the A/OPS project requirements broadly resemble the capabilities of the Royal Danish Navy's *Thetis* class vessel and the Norwegian Coast Guard's

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[13] *Parliament of Canada Act* (2007)

[14] See Appendix D and National Defence and the Canadian Armed Forces (2014a)

[15] Canadian American Strategic Review (2007)

[16] National Defence and the Canadian Armed Forces (2013a)

[17] Public Works Government Services Canada (2013a); See Appendix E for the current A/OPS reported budget and expenditures.

[18] Thomas (2007b)

[19] Canadian American Strategic Review (2007)

[20] Canadian American Strategic Review (2012)

[21] Bell (2012)

[22] Canadian American Strategic Review (2012)

[23] Bell (2012), Proussalidis (2013), and Prime Minister's Office (2014)

Svalbard,[24] the government has indicated that the A/OPS will be "more suited to Canadian environmental conditions and operational requirements."[25] For example, when compared to the Svalbard designs acquired by the government,[26] the A/OPS design will not have azipod propulsion[27,28] but will have more command and surveillance capability requiring a higher level of integration.[29]

2.1 Ice-Capable versus Icebreaker

It is important to note that A/OPS is technically not an icebreaker. It is actually an ice-capable ship.[30] Icebreakers are ships that clear a path through the ice so other ships that are not ice-capable can follow. Ice-capable ships can go through ice of various types and thickness, depending on their polar class, as icebreakers do but are not wide enough to clear a path for other ships. See the Box 1 below for a description of ship polar classes (PC). A/OPS was originally announced to be a PC 5 icebreaker.[31] It has subsequently been changed to an ice-capable ship with a bow of PC 4 and a hull of PC 5.[32]

There is a design challenge in achieving the divergent requirements of being both ice-capable and operating offshore. Icebreakers are designed to work in ice-covered water while offshore ships are designed to operate on the open seas where large waves can occur in rough weather. In addition, icebreakers traditionally have parabolic hulls which allow them to ride up over the ice and then crush it with their weight.[33] Hence, they have a higher weight-to-size ratio than ships that sail the open seas (i.e. offshore ships).[34] The parabolic hull shape and the broader beam (higher width to length ratio) than offshore ships give icebreakers "poor rough weather characteristics"[35] such as being prone to slamming.[36] In order to handle large waves, offshore ships are longer and narrower with more streamlined hulls. Also offshore ships are lighter in weight enabling them to have higher open water speed.[37] Figure 2-1 below is a picture of a Halifax-class frigate showing the sleeker design of an offshore ship. Figure 2-2 below shows the flatter and wider hull of an icebreaker.

Figure 2-1 Offshore Ship (HMCS Regina)

Source: (Levy, 2004).

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[24] Christensen (2007)
[25] CFPS Maritime Security Policy Program Research Team (2013), see as well Public Works Government Services Canada (2013c)
[26] Milewski (2013)
[27] Canadian American Strategic Review (2012)
[28] azipod propulsion system which allows the propeller unit to "rotate 360 degrees about the vertical axis" Wikipedia (2014a)
[29] Public Works Government Services Canada (2013c)
[30] National Defence and the Canadian Armed Forces (2013a)
[31] Thomas (2007a)
[32] PBO sources
[33] PBO sources and Thomas (2007a)
[34] PBO sources
[35] Thomas (2007a)
[36] Slamming occurs when the wider surface of the ship's hull relative to its length causes the ship to "slam" onto the trough of a wave after breaking through the crest of a wave.
[37] Canadian American Strategic Review (2007)

Figure 2-2 Cross-Section of an Icebreaker (Louis St. Laurent)

Source: (Chasemore & Jenssen, 2010).

Box 1: What are Polar Classes?

Transport Canada's Arctic Shipping Division works with the International Association of Classification Societies (IACS) on the unified requirements for the construction of Polar Class (PC) ships.[38] These requirements apply to ships designed to navigate the arctic, and compliant ships can be considered for a Polar Class designation.[39] IACS outlines the PC descriptions in its unified requirements.[40] The designations follow a ranking system, beginning at 1 (the most ice-capable) and ending at 7 (the least ice-capable. The table below is taken from the unified requirements.

PC 1	Year-round operation in all polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second-year ice which may include multiyear ice inclusions.
PC 4	Year-round operation in thick first-year ice which may include old-ice inclusions
PC 5	Year-round operation in medium first-year ice which may include old-ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old-ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old-ice inclusions

Thick first-year ice is thicker than 1.2 metres while medium first-year ice is less than 1.2 metres and greater than 0.7 metres.[41] Thin second-stage first-year ice is less than 0.7 metres thick and greater than 0.5 metres while thin first-stage first-year ice is less than 0.5 metres.[42] Second-year and older ice is much denser and harder than first-year ice.

2.2 Current A/OPS Program Status

After announcing the A/OPS program in 2007, the Government of Canada announced in May 2008 the definition, engineering, logistics and management support (DELMS) contract for the A/OPS. The purpose of this contract was to "develop an illustrative design (i.e. a representative concept design) […] to refine and validate the ship specification and Statement of Work to be used to select the contractor for Project Implementation."[43]

This DELMS contract was awarded to BMT Fleet Technology and STX Canada Marine, who developed and tested (simulation) a preliminary design.[44] Under the National Shipbuilding Procurement Strategy (NSPS), the A/OPS contract was awarded to Irving Shipbuilding Inc. in 2011 as part of the combatant vessel work package,[45,46] with the ships to be built at Irving's Halifax Shipyard. The project follows a "design-then-build" approach,[47] to "help mitigate cost and schedule risks in the build contract."[48]

The DELMS contract was followed by a $9.3 million follow-on design contract to Irving's Halifax Shipyard in July 2012.[49] Then in March 2013, a further definition contract of $288 million was awarded to Irving that among other things would take the A/OPS design to the point that construction could start in

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[38] Transport Canada (2010)

[39] International Association of Classification Societies (2011)

[40] Ibid.

[41] Lloyd's Register (2013)

[42] Ibid.

[43] Canadian American Strategic Review (2008b)

[44] Canadian American Strategic Review (2012), STX Canada Marine (2012)

[45] Public Works Government Services Canada (2013a)

[46] The National Shipbuilding Procurement Strategy (NSPS) announced by the Government of Canada in June 2010 aims to replace the current surface fleets of the Royal Canadian Navy and the Canadian Coast Guard. For a detailed background of the NSPS and its components, please refer to the Background section of Parliamentary Budget Office (2013)

[47] Public Works Government Services Canada (2013b)

[48] Public Works Government Services Canada (2013d)

[49] Canadian American Strategic Review (2012)

September 2015 (March 2013 plus 30 months).[50] As part of this contract, the creation of the detailed plans was outsourced to a firm in Denmark.[51]

3 Estimation Methodology

This section describes the methodologies used to derive the development and production cost estimate for the A/OPS.[52] There are four cost-estimate objectives of this report:

1. estimate the cost of building the A/OPS by identifying the person-year effort to build each of the individual ships, since production effort decreases for each subsequent ship (i.e. the learning curve[53]);
2. use the cost estimates to determine how many A/OPS can be built for the current budget of $2.8 billion;
3. determine when the budget will be spent (i.e. last ship completed) given a build schedule optimizing for cost and a start date of September 2015; and
4. determine the increased cost that would be incurred if the start date moved out to September 2016 or September 2017.[54]

3.1 Cost Estimation Overview

Since the A/OPS project has a flexible objective (i.e., six to eight ships), it is necessary to begin the analysis by constructing a model to estimate the cost of building 8 ships. If that scenario is not feasible within the stated budget, the model can then be adjusted to determine the number of ships that can be acquired within the budget.

3.2 Cost Estimation Process

The PBO employs the industry-accepted military cost estimating process best described by the United States Government Accountability Office (GAO). The GAO process is shown in Figure 3-1 below.

The GAO steps, with specific aspects of the A/OPS, are listed below:

1. Define the estimate's purpose: The purpose is to estimate A/OPS acquisition costs and schedule.

2. Develop the estimating plan: The PBO used TruePlanning® 14.0 to develop the estimate. For an explanation of the TruePlanning software application, refer to Box 2 below.

3. Define the program: The program was defined as an acquisition project to acquire six to eight ice-capable patrol ships to be built in Canada according to Government of Canada procurement rules.

4. Determine the estimating approach: The estimating approach for the project was based upon data availability and parametric analysis.

5. Identify ground rules and assumptions: The estimate will be fully documented for all alternatives (see Section 3.4).

6. Obtain the data: Physical data for CCGSs were collected (size, weight, etc.).

7. Develop the point estimate: The cost estimate was developed in an iterative fashion, based upon known values (ship class, lightweight tonnage[55]) and key parameters or cost drivers, such as Manufacturing Complexity of Structure (complexity), design repeat, project complexity and engineering complexity. This estimate reflects "Canadian realities" (i.e. it is estimated in Canadian dollars, applying Canadian

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[50] Public Works Government Services Canada (2013c)
[51] CBC News (2013)
[52] The life-time operating and support costs of the ships are excluded.
[53] See Appendix A.
[54] Naval building programs have a higher rate of inflation than either GDP or CPI inflation: see grey box below titled "Cost Escalation in Naval Procurement"
[55] Tonnes light is the weight of the vessel without fuel, crew, or cargo.

taxes, and taking into account shipyard-specific capabilities).

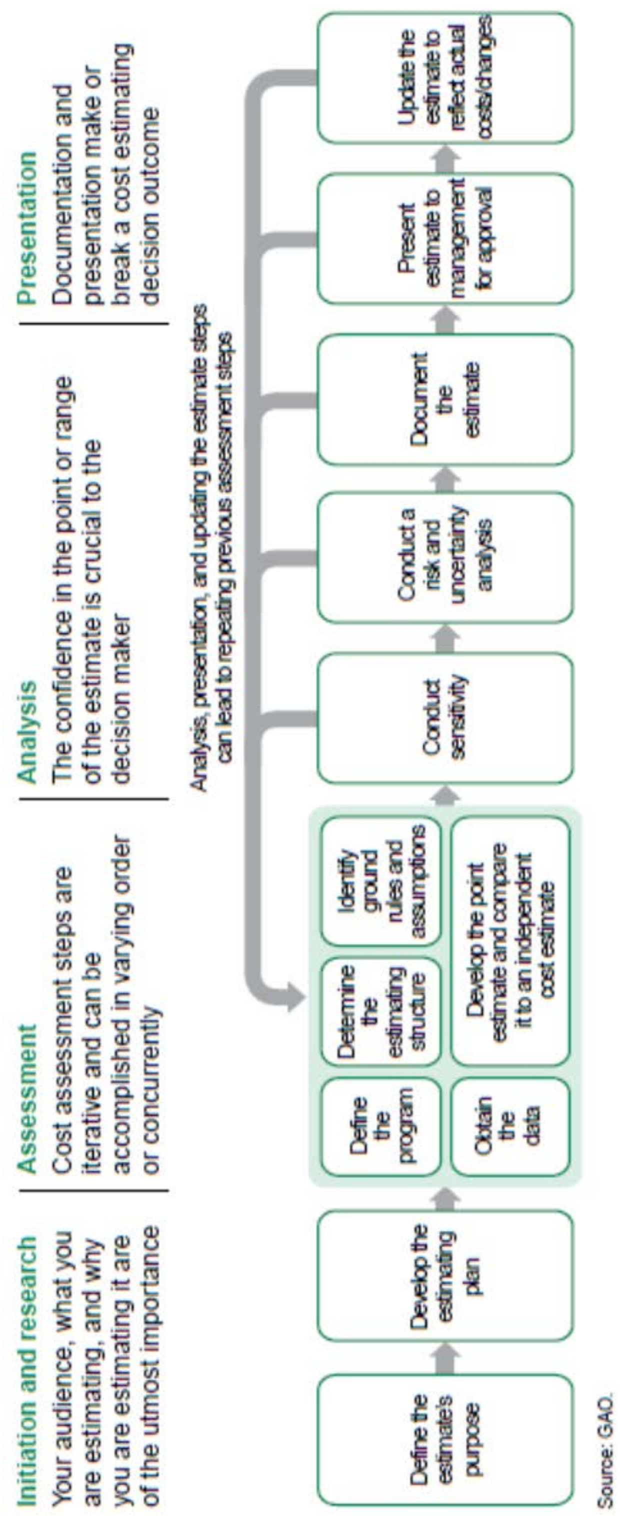
8. Conduct sensitivity analysis: Sensitivity analysis was developed around key cost drivers – weight and complexity – allowing the cost impact of changes to be measured.

9. Conduct risk and uncertainty analysis: A risk assessment/analysis was conducted following the completion of the point estimates and is documented in Section 4 Estimation Results. Risk analysis modeled a triangular distribution[56] of likely ranges of possible weight, complexity, operating specification, and engineering complexity. Uncertainty is modeled by TruePlanning which provides confidence levels for each of the cost-point estimates that it generates.

Box 2: What is TruePlanning® Software by PRICE Systems LLC?

TruePlanning® is a proprietary cost estimating tool that has applications in both military and non-military domains. It is backed by extensive military cost estimating expertise. Clients include the US Department of Defense, Sikorsky Aircraft, NASA, BAE Systems, Gulfstream, United Technologies and Boeing. For a full list, see: <http://www.pricesystems.com/success/customer_overview.asp>. The PBO published its first report using this software in February 2013. The report entitled *Feasibility of Budget for Acquisition of Two Joint Support Ships*[57] provides significant detail with respect to the software and its use in the development of a cost estimate. This report will make reference to the original where appropriate; however readers requiring additional information may wish to consult the original report or the PRICE Systems LLC website.[58]

Figure 3-1 GAO Cost Estimation Approach



Source: (United States Government Accountability Office, 2009).

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[56] TruePlanning™ uses triangular distributions to randomize possible inputs in order to generate confidence intervals for the risk assessment.
[57] Parliamentary Budget Office (2013)
[58] http://www.pricesystems.com/

3.3 Data Collection and Data Sources

The data used in the analysis of the A/OPS project came from a variety of sources. Data about weight and costs from previous similar projects, and other design specifications were entered into the model. The various data collected are listed in Table 3-1 below.

Table 3-1 Data Collection Summary

Documents	Source
A/OPS Project Details	National Defence and the Canadian Armed Forces (2013a)
Collective agreement between Local No. 1 Industrial Union of Marine and Shipbuilding Workers of Canada and Halifax Shipyard (2012-17)	Local No. 1 Industrial Union of Marine and Shipbuilding Workers of Canada
"As delivered" weights of similar Coast Guard ships, from their stability manuals	PBO Sources
Costs of similar Coast Guard ships	Information request IR0127[59]
A/OPS Statement of Requirements	PBO Sources

3.4 Ground Rules and Assumptions

The data ground rules and assumptions for the estimate were that it:

- includes development and production costs
- is calculated in "as spent" Canadian dollars[60]
- assumes 3.3% annual cost escalation (see Box 3 below)
- assumes ship weight of 6,400 tonnes
- assumes one development ship[61] and 5 to 7 production systems (a system is an individual ship)
- assumes development began March 1, 2013
- assumes construction of development ship will begin September 1, 2015 and will be completed by December 1, 2018
- assumes the remaining ships will be completed by December 1, 2024
- assumes 10% profit on the contract
- assumes 15% HST on the contract

Box 3: Cost Escalation in Naval Procurement

There are two different forms of cost escalation that affect naval procurement, both of which are greater than consumer price index (CPI) inflation. One form is the cost escalation between different generations of the same type of ship. The cost of a newer ship version in comparison to a previous version will have had an annual cost escalation between 3 and 7% above CPI inflation.[62] The PRICE modeling software takes such generational shifts into account. The second form is the cost escalation during the building of multiple versions of the same ship. This cost escalation is 1.3% above CPI.[63] For the costing of A/OPS, CPI inflation was assumed to be the Bank of Canada target rate of 2%, to which 1.3% was added to arrive at 3.3%.

3.4.1 Discussion on Profit Margins

The profit margin, which will be part of Irving`s contract with the government, is not public knowledge since it is subject to negotiations between the Government of Canada and Irving. That said, under the NSPS Umbrella Agreement, Irving is guaranteed a minimum amount of business to offset its $300 million investment in shipyard improvements; otherwise Canada is obligated to reimburse it.[64]

After searching for Canadian examples, the PBO was unable to locate reliable, sufficiently contemporary Canadian data on an acquisition of this nature: it has been 18 years since the last of the Halifax-class

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[59] See Appendix B for the received ship costing data.

[60] "as spent" means the dollar amount in the year the ship was built.

[61] Even though the first ship is considered a development ship, it is a real production ship and will be used in service like all the other ships.

[62] Arena, Blickstein, Younossi and Grammich (2006) and PBO calculation

[63] Congressional Budget Office (2013)

[64] Office of the Auditor General of Canada (2013)

frigates was commissioned[65] and 15 years since the last of the Kingston-class coastal defence vessels[66].

Looking outside Canada, the European experience illustrates significant variability in the average industry profit, ranging from incurred losses to between 8% and 9% profit.[67] The profit of individual organizations varies depending on the kind of ships built and repaired and the capabilities of the ship designers and builders.[68] Using the European profit range between 8% and 9% and the assumption that the $300 million shipyard capital investment is being amortized at a faster rate than industry averages (based on the umbrella agreement guaranteed minimum), the PBO selected a slightly higher profit margin of 10%.

3.5 Parametric Model Development

A parametric methodology was selected to estimate the cost of A/OPS. Parametric methodology uses statistically based equations to relate high-level technical and performance parameters, like ship displacement and size and the costs of other comparable ships, to determine an estimate of the cost of the current ship.

An alternative to a parametric analysis is a bottoms-up analysis based on a detailed specification of the ship. When the A/OPS was originally announced, the government's technical statement of operational requirements (SOR) was publicly available, but it has since been removed from the Department of National Defence (DND) website.[69] The PBO did request the A/OPS SOR from the DND but was told the SOR was outside the scope of the PBO's mandate.[70] The PBO did receive a highly redacted version by submitting a request under the *Access to Information Act*. Even if this document had not been redacted, its information appeared to be at such a high level it would not have been suitable for a bottoms-up analysis. Therefore, without detailed specifications from which to develop a bottoms-up estimate, we opted to use a parametric approach.

To build the parametric model, the PBO chose to develop a "nine-box" (described below) estimate as opposed to a detailed subsystem level estimate. The PBO's earlier cost estimate of Canada's budget for the acquisition for two joint support ships (JSS) was developed using a two-box model.[71] The "parent" node (i.e. box one) in the JSS model provided the costs of providing systems engineering and project management resources for the project, while the "child" node (i.e. box two) modeled the construction cost of the development and production ship.

However, it is not possible to differentiate between multiple production ships when analyzing models developed using the two-box model. Consequently, the PBO used a nine-box method in order to establish the learning curve adjusted costs and labour hours on a ship-by-ship basis.

A nine-box model is similar to the two-box model used in the JSS report in that there is a "parent" level that captures the systems engineering and project management tasks for the entirety of the acquisition program (box one). Instead of a single child node (box two) to model all of the ships (one development ship and the total number of production ships), the model uses one box for each of the eight ships (box two through nine). A learning curve is created by telling each box how many production units came before it.

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[65] Wikipedia (2014c)

[66] Wikipedia (2014e)

[67] ECORYS SCS Group (2009)

[68] Bjørn Guvåg, Oterhals, Johannessen, Moghaddam, Seth, Ona and Furstrand (2012)

[69] See Canadian American Strategic Review (2008a) where the link to technical statement of operational requirements is no longer working.

[70] Information Request IR0107 (2013)

[71] Parliamentary Budget Office (2013)

The following parameters were used:

- acquisition quantity was set at eight (one prototype and seven production ships);
- acquisition schedule according to the RPP; and
- system weight, which assumes that the weight of the A/OPS will be at 6,400 tonnes light (approximately 14 million pounds).

Costs were estimated in Canadian dollars with an annual inflation rate of 3.3% as discussed previously.

The key system object costs drivers are multiple site development, vendor interface complexity, and project complexity. These inputs describe the systems engineering and project management tasks required to undertake a project of this complexity. All of the model inputs are provided and described in Appendix C.

3.5.1 Data Normalization Process

The first step in parametric model development is to normalize the data that is used in the model. In the case of this analysis, it is the set of comparable ships. The PBO obtained a “database” of ship data points, which included the following fields:[72]

- Ship name
- Ship class
- Number built
- Country of origin
- Shipyard
- Year when finished construction (production date)
- Weight (tonnes light)
- Size (length, beam, draft)
- Complement (crew)[73]
- Power plant and engines
- Cost type
- Cost notes

The database included mainly Canadian Coast Guard Ships (CCGS), with production dates ranging from 1969 to present. Since the historical data was provided at the ship level, data cleansing, normalization, and calibration were also done at the ship level. Consequently, the cost estimate had to be conducted at the ship level.

The key data required to calibrate the model were the construction year, weight, and cost of the ships. Since all CCGS data were provided in consistent units of measurement and currency, minimal data normalization was required. The following section contains a brief description of the ships considered and those used for calibration.

3.5.1.1 Comparable Ships

In order to perform a parametric cost estimate, it is necessary to determine a list of ships that are similar in function to the ship being estimated.

Four classes of ships were considered as comparators: Svalbard, Thetis, Knud Rasmussen, and the existing fleet of Canadian Coast Guard ships that have various levels of icebreaking capabilities.

Since it was not possible to obtain detailed product specifications, the PBO began its research by consulting with naval experts familiar with the ship’s requirements, and comparing them to the Svalbard, the Thetis, the Knud Rasmussen, and the CCGS. The information thus obtained was used to approximate the build complexity by identifying a range of ships similar in size and capability to the proposed A/OPS. Based on these discussions, it was established that the Canadian design would differ from that of the:

1. Svalbard in a number of material ways (see Section 2 and Appendix B.1), in addition to there being no reliable cost information available;

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[72] See Appendix B.

[73] See Appendix A.

2. Thetis, which is almost half the weight, and like the Svalbard, there is no reliable cost information available; and
3. Knud Rasmussen, which is a quarter of the weight, less ice-capable, and there is no reliable cost information available.

Therefore, the most similar ships constructed in Canada are the CCGS for which there is reliable cost information available. For these reasons, the CCGS were selected as the comparable ships. A more detailed discussion on these comparison ships is provided in Appendix B.

3.5.2 Manufacturing Complexity Calibration Process

The TruePlanning software uses year of construction, weight, and cost in Then-Year dollars to calibrate the complexity based on the selected set of comparable ships. Given a particular complexity, the model can predict with a degree of certainty and accuracy, the cost of a project. It is important, therefore, to narrow down complexity to a range of potential values.

Table 3-2 below shows the results of the TruePlanning complexity analysis of the CCGS. Further details for the ships listed in the table are provided in Table B-1 in Appendix B on page 27. With a few exceptions, the heavier the ship, the higher its complexity.

Figure 3-2 below graphs the calculated complexity versus weight using the data from Table 3-2. Looking at the graph, the Louis St. Laurent (LSL) at the high end and the Griffon at the low end stand out from the others with regards to their weight/complexity ratio. Both these ships were built much earlier than the other ships (see Appendix B) and seem to follow a different complexity curve. These two ships were then excluded from a linear regression that was used to estimate the complexity of A/OPS using its weight (R^2=0.64, $p < 0.01$).The estimated complexity for A/OPS weighing 14.16 million pounds is 3.73.

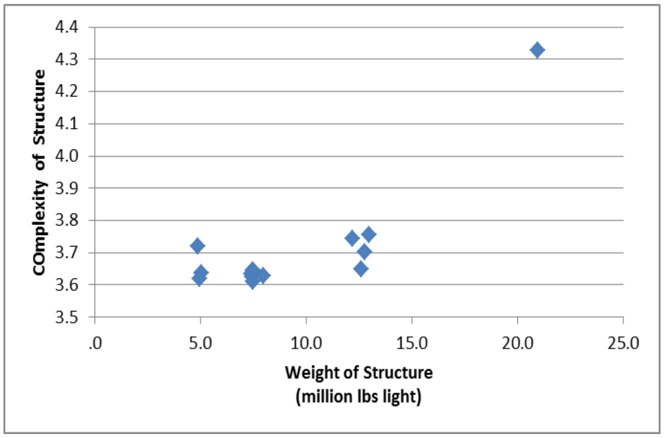
This manufacturing complexity value can be used to calculate a point estimate; however, a range of values was used to conduct the risk analysis (see Appendix F for risk inputs and Section 4 for the resulting confidence intervals).

Table 3-2 Complexity of Comparable Canadian Coast Guard Ships

Ship Name	Complexity	Weight of Structure (lbs light)	Reported Cost (then-year million$)
Louis St-Laurent	4.327	20,939,520	$170
Henry Larsen	3.755	12,992,000	$104
Amundsen	3.702	12,788,160	$ 52
Des Groseilliers	3.648	12,613,440	$ 65
Pierre Radisson	3.744	12,199,040	$ 52
Griffon	3.719	4,883,200	$ 14
Edward Cornwallis	3.634	7,403,200	$ 60
Sir William Alexander	3.626	7,443,520	$ 60
Ann Harvey	3.611	7,461,440	$ 60
George R. Pearkes	3.640	7,479,360	$ 60
Sir Wilfred Laurier	3.628	7,965,440	$ 60
Martha L. Black	3.645	7,483,840	$ 60
Samuel Risley	3.636	5,051,200	$ 41
Earl Grey	3.619	4,977,280	$ 41

Source: PBO using TruePlanning software.

Figure 3-2 Complexity versus Ship Weight



Source: PBO using TruePlanning software.

4 Estimation Results

Using the methodology and the parameters described in the previous section as well as the additional parameters described in Appendix C, a series of estimations were performed using TruePlanning software. These estimations determined a series of risk-adjusted estimates spanning a confidence interval range from 5% through 95%. TruePlanning™ calculates these ranges by varying the inputs of key cost drivers selected by the cost estimator. In this case, weight of structure, manufacturing complexity, engineering complexity, and operating specification were varied to produce the confidence intervals (see Appendix F for descriptions of these inputs and their ranges).

Box 4: Why confidence levels are important?

Cost estimating models yield two kinds of result: point estimates and confidence intervals.

Point estimates provide an anticipated cost based upon what the estimators believe to be the most likely outcome of the project. However, with complex projects such as the A/OPS, there are likely to be adjustments to the design and construction plans. In order to account for these changes, the cost estimators also run a risk analysis to assess how changes to key inputs (e.g., the weight of the ship) might impact the cost estimate. Software is used to calculate the possible combinations of inputs and to produce a range of potential cost estimates, and the resulting cost estimates are then ordered from lowest to highest. The mid-point of these estimates is called the 50% confidence level and is considered a minimum acceptable standard when selecting a budget. Organizations that are more risk-averse or that undertake more risky projects may budget at the 80% confidence level, so that 80% of the anticipated outcomes yield cost estimates less than the budget, and only 20% yield estimates greater than the budget.

Two sets of estimations were performed. The first set of estimations assumed that the construction of A/OPS would start as planned in September 2015, and the second set of estimations had the start of construction delayed by one and two years. Each will be discussed in turn.

4.1 A/OPS Cost Estimate

Risk-adjusted point estimates with confidence intervals were calculated for scenarios using four, five, six, and eight ships with construction to begin as planned in September 2015. The results are shown in tabular form in Table 4-1 and graphically in Figure 4-1 on the following page.

As can be seen from these results, it is not possible at any confidence level to build eight or six ships for the $2.8 billion budget. Only when the number of ships is reduced to five is there a confidence level 5% or higher. For five ships the confidence level is just under 20%. Therefore it is highly unlikely that building five ships is achievable without increasing the budget. With a confidence level just under 20%, it is 80% likely to go over budget. From Table 4-1, to get to a 50% confidence level for five ships, the budget would need to be increased by at least $230 million. A much more likely scenario for the $2.8 billion budget would be four ships which has a confidence level of between 50% and 55%. This would then only have a 45% to 50% likelihood of going over budget.

If the government wanted to deliver the stated minimum six ships, the budget would need to be augmented by $470 million to achieve a 50% confidence level.

Table 4-1 Estimated Total Cost of Production for Given Number of Ships*

Confidence	Total cost for # of ships (billions)			
	8 Ships	6 Ships	5 ships	4 ships
5%	$3.27	$2.84	$2.62	$2.39
10%	$3.37	$2.93	$2.70	$2.47
15%	$3.43	$2.99	$2.76	$2.53
20%	$3.49	$3.04	$2.81	$2.58
25%	$3.54	$3.08	$2.85	$2.62
30%	$3.58	$3.12	$2.89	$2.65
35%	$3.62	$3.16	$2.93	$2.69
40%	$3.66	$3.20	$2.96	$2.72
45%	$3.70	$3.23	$2.99	$2.75
50%	$3.74	$3.27	$3.03	$2.78
55%	$3.77	$3.30	$3.06	$2.82
60%	$3.81	$3.34	$3.10	$2.85
65%	$3.86	$3.38	$3.13	$2.89
70%	$3.90	$3.42	$3.17	$2.92
75%	$3.95	$3.46	$3.21	$2.96
80%	$4.00	$3.51	$3.26	$3.01
85%	$4.06	$3.57	$3.32	$3.06
90%	$4.15	$3.65	$3.39	$3.13
95%	$4.27	$3.76	$3.50	$3.24

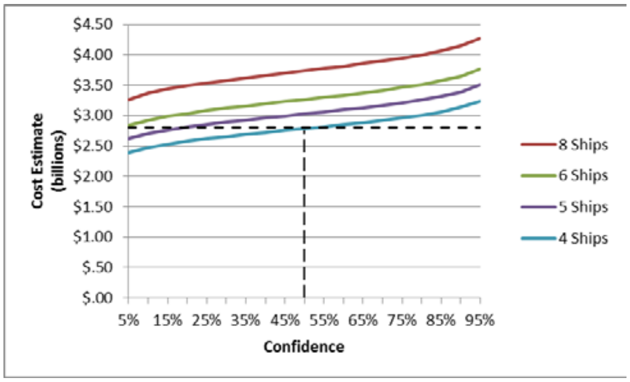
*green indicates within budget

Source: PBO using TruePlanning software.

4.1.1 Delivery Schedule with No Delay

Since the government hasn't announced a planned delivery schedule for the A/OPS, the PBO used the delivery schedules of previous Canadian navy ships. The PBO investigated the delivery schedules of the Kingston-class patrol ships which were built during the 1990s and the Halifax-class frigates that were built during the late 1980s through the mid-1990s. Generally, two Kingston-class patrol ships were delivered each year per shipyard, but they are considerably smaller ships weighing in at approximately 1,000 tonnes versus the 6,400 tonnes for the A/OPS.[74] The Halifax-class frigates are a closer comparable with a weight of 4,800 tonnes and a delivery schedule of one per year per shipyard.[75] It was assumed that the A/OPS would follow a similar delivery schedule to that of the Halifax-frigates with one being delivered each year.

Figure 4-1 Ship Cost as a Function of Confidence Level



Source: PBO using TruePlanning software.

TruePlanning software estimates the cost optimal length of time to construct each production ship (ship number two through seven) at 30 months. Estimating the cost optimal construction time for the development ship (ship number one) is very sensitive to ship weight and other factors. Given this sensitivity, providing a delivery month would be too misleading. For this reason, the estimated delivery of the development ship is listed only as likely to be in 2018 (centred on September of that year).

The estimated delivery dates and construction effort for each ship are shown in Table 4-2 below. A bar chart illustrating the estimated learning curve reduction in effort to build each ship is shown in Figure 4-2 below.

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[74] Wikipedia (2014e) and PBO sources

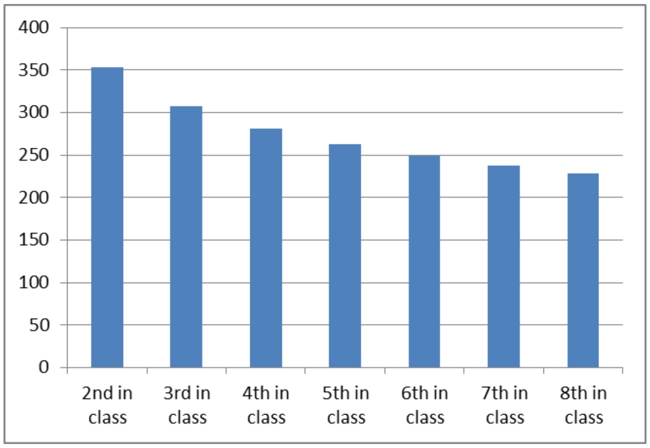
[75] Wikipedia (2014c)

Table 4-2 Ship Delivery Dates

Ship number	Delivery Date	Effort in People Years[76]
1	Likely in 2018	See note[77]
2	January 2019	353
3	January 2020	308
4	January 2021	281
5	January 2022	262
6	January 2023	249
7	January 2024	238
8	January 2025	229

Sources: PBO and TruePlanning software.

Figure 4-2 Effort in People Years to Build each Ship



Source: PBO using TruePlanning software.

The construction effort for each ship is estimated by TruePlanning software. It assumes 1,824 hours per person per year.

Notice how the effort decreases with each ship. This is the result of “learning”, and the rate of learning is illustrated by the learning curve. A shipyard can use this decrease in effort to:

1. reduce the length of time it takes to build the ship while retaining the same number of employees;
2. reduce the number of employees and take the same length of time to build the ship; or
3. a combination of 1 and 2 (e.g. less time and fewer employees).

The PBO assumed that the shipyard would deliver one ship per year (as shown in the table) similar to previous ships of a similar size.[78] It is estimated to take 30 months to build ship number 2. For ships 3 through 8, no assumptions were made regarding whether they would take less time or fewer employees or a combination of both.

4.1.2 A/OPS Cost Estimate – One- and Two-Year Delay

The PBO also investigated the effect a delay in starting construction would have on the program. The primary effect of delay is inflation such that the government will be spending the same amount ($2.8 billion) but getting less. Since inflation on military construction is greater than the consumer price index (CPI), delays in military projects have a greater effect on the budget than normally would be expected.[79] As described earlier, the assumption used in the analysis was a 3.3% escalation rate.

To investigate the effects of delaying the project, estimations were carried out assuming one- and two-year delays in the start of construction for three and four ships. This means construction would start in September 2016 or September 2017. The results are shown in tabular form in Table 4-3 and in graphical form in Figure 4-3 below.

A delay for the case of building five ships is not presented since a delay of even one year would reduce the confidence level to less than 15%.

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[76] Construction effort only

[77] Estimating only the construction effort for the first ship is not reliable since a large part of the effort is the engineering effort in addition to the construction effort. A combined estimate is 2,000 person years.

[78] See the delivery schedule for the previous Halifax-class frigate program - Wikipedia (2014c)

[79] See grey box on Cost Escalation in section 3.4 on page 9.

With a one-year delay, the confidence level for four ships drops from between 50% and 55% to 45%. This drop adds risk to achieving the four ships within the allotted $2.8 billion budget. If there is a two-year delay, the confidence level drops to between 35% and 40%. Realistically, if the A/OPS project is delayed by two years, it is likely that only three ships can be built within the existing budget.

It should be noted that "start of construction" is assumed to mean a substantive start as opposed to a ceremonial start. When construction starts and finishes has a material impact not only on the cost of A/OPS but on CSC as well. For a discussion on these CSC considerations, see Box 5 below.

Table 4-3 Estimated Cost of 3 and 4 Ships with One- and Two-Year Delays to Construction Start*

Confidence	Total cost for # of ships (billions)			
	Delayed one year		Delayed two years	
	4 Ships	3 Ships	4 ships	3 ships
5%	$2.44	$2.20	$2.49	$2.24
10%	$2.52	$2.28	$2.57	$2.32
15%	$2.58	$2.33	$2.63	$2.37
20%	$2.62	$2.38	$2.67	$2.42
25%	$2.66	$2.41	$2.71	$2.46
30%	$2.70	$2.45	$2.75	$2.49
35%	$2.74	$2.48	$2.79	$2.52
40%	$2.77	$2.51	$2.82	$2.56
45%	$2.80	$2.54	$2.85	$2.59
50%	$2.83	$2.58	$2.89	$2.62
55%	$2.87	$2.61	$2.92	$2.65
60%	$2.90	$2.64	$2.95	$2.68
65%	$2.94	$2.67	$2.99	$2.72
70%	$2.97	$2.71	$3.03	$2.75
75%	$3.01	$2.75	$3.07	$2.79
80%	$3.06	$2.79	$3.11	$2.84
85%	$3.12	$2.84	$3.17	$2.89
90%	$3.19	$2.91	$3.24	$2.96
95%	$3.29	$3.01	$3.35	$3.06

*green indicates within budget
Source: PBO using TruePlanning software.

Box 5: CSC Considerations

Due to the government's stated objective of having the A/OPS as "stepping stones"[80] to the more complex CSC, a brief discussion of their scheduling interactions and implications is presented here.

The expression "stepping stones" implies that the experience gained by the shipyard in building A/OPS will be retained and then benefit the CSC. Furthermore, there is an assumption that there will be shared overhead costs between the two projects as A/OPS ramps down and CSC ramps up.

Currently, the first CSC is scheduled to be delivered in the "mid 2020s".[81] For illustrative purposes it is assumed that this means sometime in 2025. Assuming it would take four years to build (see Appendix G), the CSC would need to start construction in 2021 in order to be commissioned in 2025. Currently, this lines up nicely with the estimated completion date of the fourth A/OPS, which is estimated to occur in 2021 (see Table 4-2 above). If for some reason the CSC program is delayed, such that construction doesn't start in 2021, then it is likely that the shipyard will start to lose productivity during the delay due to lay-offs and attrition. In addition, there will be a reduction in the shared overhead cost benefit between the two projects.[82] While this would have no fiscal impact on the A/OPS project, it is likely to increase the cost of the CSC project.

To summarize, given the $2.8 billion A/OPS budget constraint, A/OPS is estimated to be finished in 2021. If the CSC doesn't start construction in 2021, the experience gain and shared overhead benefits of the A/OPS will likely decrease, increasing the overall cost of the CSC.

The one possible upside (if one could call it that) of a construction start delay is that the Irving shipyard may not be idle if the CSC construction start date slips out. It should be noted that a delay in the CSC would likely reduce the number of CSCs that could be built due to cost inflation.

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[80] Public Works Government Services Canada (2013c)

[81] National Defence and the Canadian Armed Forces (2014b)

[82] Since the CSC build contract hasn't been signed, all costs under the umbrella agreement are assumed to be covered by A/OPS. See section 3.4.1.

Figure 4-3 Ship Cost versus Confidence Level for Delayed Construction Start

Source: PBO using TruePlanning software.

4.2 Sensitivity Analysis

In order to describe the impacts of key cost drivers on the acquisition budget, the PBO undertook sensitivity analysis of the cost estimation model for the acquisition of four ships.

A sensitivity analysis illustrates the financial impact of changing a single cost driver and holding all other inputs constant. While it is possible to present analysis on every model input, for brevity, only the critical drivers are presented and explained here: weight of structure, manufacturing complexity, operating specification, and engineering complexity (see Appendix F).

The sensitivity analysis was run using the previously described risk-adjusted estimate methodology and reporting results at the 50% confidence level. This assumes that even though the model input is being varied, its risk range as described in Appendix F hasn't been changed. Not changing the risk range for the model input results in reduced cost variation.

Lastly, each of the sensitivity cost variations described in the following subsections are additive and multiplicative. For example, if the weight of the ship is increased as well as the ship's manufacturing complexity, both of these changes add their own increase in cost plus some additional cost due to the interaction between the two factors.

4.2.1 Weight Sensitivity

Cost estimators typically undertake sensitivity analysis on the weight of a ship because of the likelihood that actual weight of the ship will differ from the designer's estimate. The intent of this analysis is to determine the degree to which variation in the weight of the ship changes the cost estimate.

Cost of ships increase with weight for primarily two reasons. The obvious reason is that steel costs money and the heavier the ship the more steel there is. The more subtle reason is that additional weight is a correlate for additional functionality. As more things than were originally planned are added to a ship, the more it will weigh. These additional things cost money. Also, at a certain point, adding more weight will necessitate propulsion system changes and additional fuel capacity if the ship is to cruise at the same speed and for the same duration.

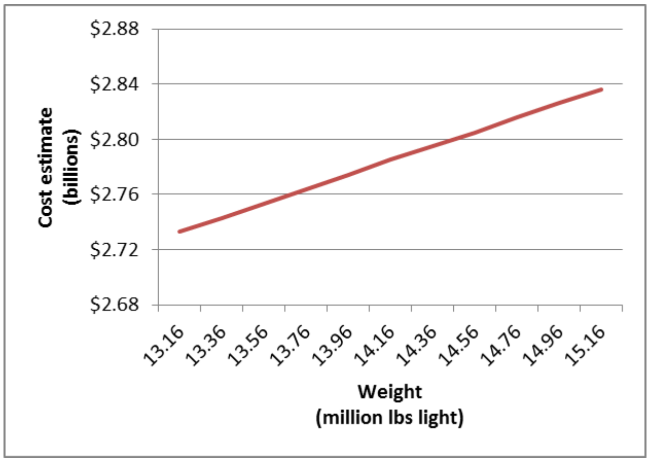
Although the weight of the ship can be a significant cost driver, the sensitivity analysis illustrates that a slight reduction in the weight of the A/OPS is unlikely to render the ship substantially more affordable. In simplest terms: a slight over-estimation of weight multiplied by four ships is insufficient to produce another ship. However, an under-estimation of the weight could put the fourth ship at risk.

The effects on the cost of A/OPS based on changing its weight at the 50% confidence level are presented in Figure 4-4 below.

The current planned weight of A/OPS is 14.16 million pounds. In the figure below, this lines up with a cost of $2.78 billion. If A/OPS weight increases to 15.16

million pounds, the cost of four ships is estimated to be $2.84 billion at 50% confidence.

Figure 4-4 Effect of Ship Weight on Cost for 4 Ships



Source: PBO using TruePlanning software.

The range of weights presented in the sensitivity analysis represents a ±7% difference at the low and high end. If the weight increases by the maximum amount (15.16 million pounds), the confidence level that four ships can be built for the $2.8 billion drops to 45%. At the low end, if the weight of the ship is reduced by 7%, the savings are not sufficient to build another ship.

It is important to note that reducing a ship's weight while holding its complexity constant may not be a valid assumption. This is because reducing a ship's weight often represents a trade-off between capability and complexity. If weight is reduced while holding capability constant, complexity will necessarily increase resulting in a higher cost. Reducing a ship's weight doesn't mean that you get the same ship but with everything a bit smaller; the resulting smaller ship will have either less operational capability or higher complexity.

4.2.2 Manufacturing Complexity Sensitivity

The cost estimation model is sensitive to the complexity value because it is the input which describes the level of technology contained in the ship, the density of the build, and consequently the amount of effort required to design and to construct the ship. As presented in section 3.5.2 on page 12, the majority of the CCGS were found to have complexities in the 3.6–3.8 range, and using linear regression, a complexity of 3.73 was selected for this model.

As illustrated in the Table 4-4 below, the A/OPS project would be more affordable if the complexity were lower. However, the historical CCGS data does not support the hypothesis that an ice-capable patrol ship can be of a lower complexity than 3.65. In fact, the opposite may be true as the hybrid nature of the ship could increase its complexity, thereby increasing its cost.

Table 4-4 Effect of Complexity on Cost for 4 Ships

Complexity	Estimated Cost (billions)	Notes
3.65	$2.70	CCGS (excluding the LSL) were within this range
3.69	$2.74	
3.73	$2.78	
3.77	$2.83	
3.81	$2.88	Upper range included to reflect uncertainty of building a hybrid ship

Source: PBO using TruePlanning software.

4.2.3 Operating Specification

The operating specification refers to the equipment's planned use (e.g. commercial shipping vs. naval vessel).The PBO selected an input that reflects the expected reliability of A/OPS (i.e. 1.5, see Appendix

C). For a discussion of the various values for "operating specification" see Appendix F. It is possible that some or all elements of the ships may be constructed to slightly higher or lower specifications, though going above 1.6 which is the mid-point for military ships is unrealistic. With this in mind, operating specification was varied between 1.2 (mid-point for a commercial ship) and 1.6. A value of 1.2 would reduce the cost of acquisition of four ships by $340 million and a value of 1.6 would increase the cost by $130 million.

4.3 Engineering Complexity

The engineering complexity value represents a measure of the complicating factors of the design effort as they relate to the experience and qualifications of the engineering design team. The PBO selected a "middle of the road" assumption with respect to this input (i.e. a value of 1.1). The ranges selected for the values reflect both optimistic and pessimistic assumptions about the competence of the engineering design team. Varying this input (between 1.0 and 1.2) has a maximum impact of approximately ± $65 million on the acquisition of four ships. See Appendix C.1 on page 35 for a more in-depth discussion of engineering complexity.

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Appendix A Terminology

Complement: The term “complement” is used to describe the number of people who will be manning the ship. This is an important variable when predicting the size or complexity of the A/OPS because the distance between ports increases the space needed to store supplies and waste. The A/OPS will have a crew of 45.[83]

Unit Learning Curve: As shipyard laborers become more familiar with the construction of a ship, the fewer hours they require to construct subsequent ships in its class. Consequently, cost estimators must account for improvements in the efficiency of the workforce over time. One way to do so is to use a unit learning curve formula to estimate how many hours will be required to produce the subsequent ships.[84]

$$Y_x = Kx^{log_2(b)}$$

The following example illustrates how a unit learning curve of 95%[85] would change the number of direct labour hours

- Let K be the number of direct labour hours to produce the 1st production unit of a ship
- Let Y_X be the number of direct labour hours to produce the 8th production unit of a ship
- Let x be the unit number; 8 for the 8th ship
- Let b be the learning percentage; assumed to be 95% (0.95) for this project

$$Y_8 = K(8)^{log_2(0.95)}$$

$$Y_8 = K(0.857)$$

$$Y_8/_K = 85.7\%$$

Consequently, we would predict that the direct labour hours required to manufacture the 8th ship would be 85.7% of the hours required for first ship.

For the model used to estimate the cost of the A/OPS, the PBO left the learning curves unbounded so that the TruePlanning software could apply the appropriate values based on historical programs.

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[83] STX Canada Marine (2012)

[84] Chase (2001)

[85] 95% is used for illustrative purposes. For the actual analysis, the software selected the learning curve.

Appendix B Ship Data

This appendix discusses the four classes of ships which were considered as possible comparables for A/OPS. They were: Svalbard, Thetis, Knud Rasmussen and Canadian Coast Guard Ships. Each is discussed below.

B.1 Svalbard-Class Ships

In order to balance the conflicting requirements of being both ice and offshore capable, the current A/OPS design will resemble the Norwegian ship Svalbard, but with different ship systems and a modified hull design.[86] The Svalbard design is a compromise between the two capabilities by having a more streamlined hull but strengthened in order to go through ice. Since the A/OPS hull design is not parabolic, it breaks ice by pushing through ice rather than riding up on top and crushing it as a typical icebreaker would do. Therefore it is the bow that must break through the thick (greater than 1.2 metres) first-year ice. This is why the hull only needs a PC 5 classification (to handle hitting old-ice inclusions) while the bow is PC 4.[87]

The Svalbard is listed as a DNV Class notation Icebreaker POLAR-10.[88] DNV stands for Det Norske Veritas which is a Norwegian ship classification and standards firm (comparable to Lloyd's Register[89]). POLAR-10 means that the ship can go through first-year ice up to one metre in thickness with old-ice inclusions but is not expected to ram the ice as would a true icebreaker. [90] Based on this description, it is assumed that a ship with a DNV POLAR-10 classification is close to a PC5 classification (1-metre thick ice versus 1.2-metre). So from a polar classification perspective, the bow of the A/OPS is over one level above that of the Svalbard. This higher classification will result in a more expensive hull.

Another difference between the Svalbard and the A/OPS is that the Svalbard is equipped with an azipod propulsion system which allows the propeller unit to "rotate 360 degrees about the vertical axis"[91], while A/OPS has a conventional and less expensive system of "twin shaft-driven screws and rudders".[92]

The Svalbard and A/OPS also differ in regards to their respective command and surveillance capability and level of integration. For A/OPS, these capabilities are greater than for the Svalbard, which will in turn increase the A/OPS cost.[93]

As the previous paragraphs demonstrate, the Svalbard has aspects that would make it both less expensive (lower ice capability and less command and surveillance capability/integration) and more expensive (azipod propulsion) than the A/OPS. It also has the same displacement as the A/OPS at 6,400 tonnes.[94] From a high-level, these differences might be considered inconsequential such that the Svalbard would be a useful data point for modeling the A/OPS. There are publicly available documents which put the cost for the Svalbard between $80 and $100 million.[95] These costs are considered unreliable since they likely don't include the full cost of the ship design, some equipment systems fitted in the ship and subsidies to the Norwegian shipyards.[96] With no reliable costing data available for the Svalbard, it could not be used.

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[86] Public Works Government Services Canada (2013c)

[87] A ship is assigned its overall Polar Class based on its weakest classification. In the case of the A/OPS, since the hull is PC5, the ship will be assigned PC5 even though the bow is PC4.

[88] homelandsecurity-technology.com (2014)

[89] Familiarly known as Lloyd's Register of Shipping.

[90] Det Norske Veritas (2009)

[91] Wikipedia (2014a)

[92] Canadian American Strategic Review (2012)

[93] PBO sources

[94] homelandsecurity-technology.com (2014) and PBO sources

[95] See Milewski (2013), Wikipedia (2014f)

[96] There has been public discussion on the Svalbard costing $100M CAD in 2001 dollars (Milewski (2013) and Public Works Government Services Canada (2013c). This cost is not representative due to large public subsidies of the Norwegian shipyards at the time (ibid.).

B.2 Thetis-Class Ships

The Thetis class of ships were built by Denmark in the early 1990s to be ice-capable offshore patrol vessels (OPV) capable of going through ice with a maximum thickness of 80 cm.[97] Due to its small size (3,500 tonnes[98] versus 6,400 tonnes[99] for A/OPS), light ice capability, and the lack of costing data, it was not used as a comparable.

B.3 Knud Rasmussen-Class Ships

The Knud Rasmussen class is another Danish OPV with the first ship commissioned in 2007.[100] The Knud Rasmussen class is even lighter (1,700 tonnes) and less ice capable (70 cm maximum ice thickness) than the Thetis class.[101] For these reasons it wasn't considered comparable to the A/OPS.

B.4 Canadian Coast Guard Ships

In the end, the ships that were best suited to compare against were the existing fleet of Canadian Coast Guard (CCG) icebreakers and ice-capable ships. Table B-1 below has a list of these ships except for the Terry Fox. The Terry Fox was excluded since it was originally built for Gulf Oil and was later bought by the CCG.[102] The original cost to build the Terry Fox was not available which therefore excluded it as a comparable.

The CCG ships were suitable to compare against for several reasons. First, they were all built in Canadian shipyards as the A/OPS will be. This reduces the likelihood of inconsistencies due to country-specific differences such as labour costs and taxes. Second, they were designed for icebreaking in Canadian conditions. Operating temperatures vary depending on the climate conditions of where the ships must operate.[103] Third, the displacements of the medium icebreakers (Amundsen, Des Groseilliers, Henry Larsen, Pierre Radisson) are quite similar to the estimated displacement of A/OPS. Having similar data points helps reduce the estimation error. Fourth, the cost to build these ships was available from the CCG. More importantly, the PBO was confident that the costs were calculated consistently across the ships, which is necessary to have an accurate calibration of the modelling software.

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[97] naval-technology.com (2014)

[98] Christensen (2007)

[99] PBO sources

[100] Danish Naval History (2008)

[101] Canadian American Strategic Review (2008c)

[102] Wikipedia (2014b)

[103] The water around the Svalbard islands is more temperate due to the influence of the Gulf Stream. Wikitravel (2014)

Table B-1 Comparable Canadian Ship Specifications

Ship Name	Year	Old Class	New Class	Region	Builder	Original Cost	Light Displacement Tons (As Delivered)
Louis S. St-Laurent	1969	1300	Heavy Icebreaker	Atlantic	Canadian Vickers	$169,644,954	9348
Pierre Radisson	1978	1200	Medium Icebreaker	Central and Atlantic	Versatile	$52,245,631	5446
Amundsen	1979	1200	Medium Icebreaker	Central and Atlantic	Burrard	$52,077,650	5709
Des Groseilliers	1982	1200	Medium Icebreaker	Central and Atlantic	Port Weller	$64,557,000	5631
Henry Larsen	1987	1200	Medium Icebreaker	Atlantic	Versatile	$104,455,000	5800
Griffon	1970	1100	High Endurance Multi-Tasked Vessel	Central and Atlantic	Davis	$13,713,362	2180
Edward Cornwallis	1986	1100	High Endurance Multi-Tasked Vessel	Atlantic	Marine Industries	$60,106,700	3305
George R. Pearkes	1986	1100	High Endurance Multi-Tasked Vessel	Atlantic	Versatile	$60,213,459	3339
Sir Wilfrid Laurier	1986	1100	High Endurance Multi-Tasked Vessel	Western	Collingwood	$60,167,230	3556
Martha L. Black	1986	1100	High Endurance Multi-Tasked Vessel	Central and Atlantic	Versatile	$60,106,700	3341
Sir William Alexander	1987	1100	High Endurance Multi-Tasked Vessel	Atlantic	Marine Industries	$60,106,700	3323
Ann Harvey	1987	1100	High Endurance Multi-Tasked Vessel	Atlantic	Halifax Dartmouth	$60,106,700	3331
Samuel Risley	1985	1050	Medium Endurance Multi-Tasked Vessel	Central and Atlantic	Vito Steel	$41,409,245	2255
Earl Grey	1986	1050	Medium Endurance Multi-Tasked Vessel	Atlantic	Pictou	$41,402,500	2222

Sources: PBO sources and PBO information request 0127. See http://www.pbo-dpb.gc.ca/files/files/IR0127_FOC_AOPS_Financial_Data_EN.pdf.

Appendix C Model Inputs

TruePlanning differentiates between costs associated with producing the development ship, or first ship in class, and costs associated with producing actual production units—those ships in class that follow the development unit. This distinction is made because the cost associated with producing the first ship in class is significantly higher than that of the production units that follow, and only production ships benefit from the cost savings derived from a learning curve.

The A/OPS project is intended to acquire between six (one development and 5 production) and eight ships (one development and 7 production). Consequently, the structure of the model is as follows:

- A/OPS Project
  - Systems Engineering and Project Management
    - Development Ship
    - 2nd in class
    - 3rd in class
    - 4th in class
    - 5th in class
    - 6th in class
    - 7th in class
    - 8th in class

Table C-1 Details of the Inputs entered into the TruePlanning Model used to estimate total cost

Level	Variable	Input(s)	Explanation
Systems Engineering and Project Management	Quantity per next higher level	1	The quantity per next higher level indicates that the model should include one of each ship in the model (e.g. one development ship, one 2nd in class, etc.).
	Operating specification	1.50 (High Reliability)	The operating specification refers to the equipment's planned use (e.g. ground military, submarines, air to air missiles, etc.). It has an

Level	Variable	Input(s)	Explanation
			impact on cost, as different operating specifications involve different requirements with respect to portability, reliability, structuring, testing, and documentation. TruePlanning attributes a value to each operating specification, and this value has a significant impact on development engineering costs. Since the A/OPS does not align with any single category of equipment, the Function Mode was used to calculate the operating specification of the platform. Based on a higher than average reliability requirement, the operating specification was estimated at 1.50.
	Multiple site development	4.5	The multiple site development value describes communications challenges presented by teams operating in multiple geographic locations. Communication affects productivity and becomes more significant when development personnel work from different sites on the same equipment. This value is a function of the number of and quality of communication between the active locations for the program. In this case, there will be multiple active locations (i.e. the client (DND), a number of design phase contractors and subcontractors (e.g. Odense Maritime Technology in Denmark[104,105]), and Irving. Federal procurement rules put certain restrictions on the ability of federal employees to communicate with contractors. Since the government must participate in communications between the

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[104] Irving Shipbuilding Inc. (2013)

[105] Doucette (2013)

Level	Variable	Input(s)	Explanation
			shipyard and the designer, there will be additional time and costs. Where the communication between multiple locations is characterized as poor, TruePlanning ascribes a value of 4.5.
	Vendor interface complexity	Very high vendor interface and supervision requirements	The vendor interface complexity describes the degree and intensity of requirements to interface with vendors or subcontractors on the project. It ranges from low to very high. Technical reviews, audits, quality assurance requirements, and formal acceptance testing in the context of this procurement will be significant as compared with non-military procurements. These requirements will be monitored through a series of "gates" or milestones used to track the progress of the project against its objectives. As such, vendor interface complexity will be very high.
	Project complexity factor	75 High; Indicates planning and oversight levels typical in a mid-size to large or moderately complex project.	The project complexity factor is reflective of the planning and oversight activities necessary to successfully manage the project. The project complexity factor is used to predict the amount of the oversight and planning required to successfully manage the project. The value of this factor ranges from 0 to 100: a value of 0 will result in no planning and oversight calculations; a value of 50 results in the typical values for planning and oversight activities in a small to mid-size project; and, a value of 100 results in values typical for a large or highly complex project. A level of high was selected because of the complexity of managing a government procurement of a unique vessel requiring numerous audit functions and sign-offs.

Level	**Variable**	**Input(s)**	**Explanation**
	Number of vendors	5	Number of vendors indicates the number of outside sources that will be supplying equipment, software, or services. The value of this input influences the effort for system engineering activities. While the exact number of vendors that will be involved in this project is unknown, there will, at the very least, be five tier one vendors: Lloyds Register Canada Ltd, Lockheed Martin Canada Inc., Odense Maritime Technology, General Electric Energy Conversion, and Fleetway Inc.[106]). As such, the number of vendors was set at 5.
Acquisition	Start date	March 2013	This date is taken from the most recent Report on Plans and Priorities (RPP).
	Weight of structure	14,160,000 lbs	The weight of structure indicates the weight of the mechanical/structural portion of the equipment. As weight increases, the amount of effort associated with engineering increases, tempered by the impact of increased or decreased technological maturity. Weight increases are also result of increases in effort and material required for prototype development. The weight used in the A/OPS estimation model was sourced from various briefing materials through the design process.[107]

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[106] Information Request IR0155 (2014)
[107] STX Canada Marine (2012)

Level	Variable	Input(s)	Explanation
	Manufacturing complexity of structure (complexity)	3.73	The complexity represents a technology index for the structural portion of the equipment and is linked to the operating specification. Manufacturing complexity is a measure of the equipment's technology, its producibility (material machining and assembly tolerances, machining difficulty, surface finish, etc.), and yield. The manufacturing complexity of the A/OPS ship was arrived at using attributes data obtained from public sources, and through an information request to the Department of Fisheries and Oceans.[108] These data were calibrated using TruePlanning™ and its companion applications.[109]
	Per cent of new structure	Development ship: 75% Subsequent ships: 0%	The per cent of new structure represents the amount of new structural design effort based on design tasks that already exist or may have already been completed. The value for the per cent of new structure is a cost driver for the development engineering activity for the equipment. While the government did acquire the designs of the *Svalbard*, the government's requirements of the A/OPS (e.g. lighter, different propulsion system) were markedly different. The model assumes that new structure requires full development engineering activity and that existing structure requires no engineering at the component level.

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[108] Ships listed in Appendix B

[109] Refer back to 3.5.2 for a detailed explanation of the calibration process.

Level	Variable	Input(s)	Explanation
	Per cent design repeat for structure	40%	This input captures the repeated use of design components reflecting the symmetry of the ship's hull. Per cent of design repeat is determined by the ratio of repeated hardware to unique hardware. A completely symmetrical ship would result in 50% design repeat. Although the hull itself is symmetrical, some internal components may not be (e.g. communications and weaponry systems).
	Engineering complexity	1.1 (see discussion below) New design, existing technology Mixed experience, some product familiarity	The engineering complexity value represents a measure of the complicating factors of the design effort as they relate to the experience and qualifications of the engineering design team. As skill set and experience decrease or as the engineering challenges increase, the costs for development engineering increase. Development manufacturing and development tooling and test activities also increase with increasing complexity as the engineers and assemblers grapple with implementing and testing prototypes designed by less experienced personnel or under less than ideal design conditions. Engineering complexity is a significant driver in the development engineering effort. Engineering complexity has no impact on production costs, but does have a non-linear impact on development costs.
	Labour learning curve	Software projection based on historical programs	This learning curve describes the rate at which production costs decrease due to improved labour efficiency.

Level	Variable	Input(s)	Explanation
	Materials learning curve	Software projection based on historical programs	This learning curve describes the rate at which production costs decrease due to reductions in the cost of material.
	Manufacturing process index	2.920	The TruePlanning™ software enables the user to calculate an adjustment factor to reflect the degree of manual labour required to manufacture a product. In the case of the A/OPS, it is necessary to adjust this value as ship building is labour intensive and capable of only limited automation.
	Development engineering	Start: 2013 End: 2018	These dates are taken from the RPP.[110]
	Production manufacturing	End: 2024	This date is taken from the RPP.[111] The model schedule was developed to meet this completion date.
Other	Labour rates	Professional labour rates as per price model, skilled labour as per collective agreement	TruePlanning contains pre-existing labour unit costs for Canadian production. These figures were adjusted to reflect the most recent collective agreement negotiated between Irving and its employees.

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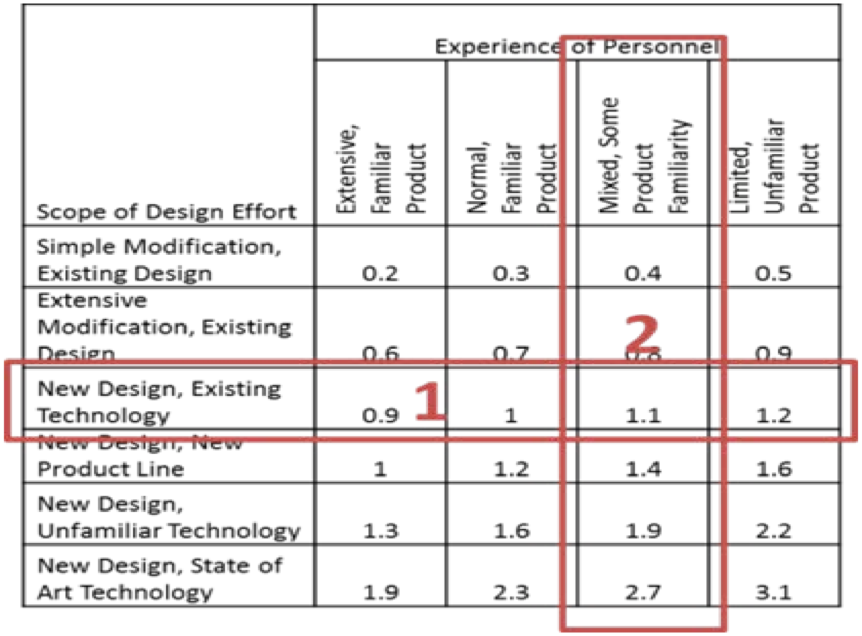
[110] See Appendix D.

[111] See Appendix D.

C.1 Discussion of Engineering Complexity

Table C-2 presents a modified version of TruePlanning's engineering complexity selection criteria. Experience of personnel was selected as "mixed with some product familiarity". Irving is an operating shipyard, but it hasn't built ice-capable ships in almost 20 years plus there will be a large number of new staff hired as the shipyard expands to build A/OPS. Scope of design effort was selected as "new design" and "existing technology". TruePlanning's terminology defines "new design" as a ship that hasn't been built before. Since A/OPS hasn't been built before, it is a new design. Since A/OPS is based on the Svalbard, it is considered existing technology. The intersection of "new design, existing technology" and personnel "with mixed skill, with some product familiarity" results in an engineering complexity value of 1.1.

Table C-2 Engineer Complexity Determination



	Experience of Personnel			
Scope of Design Effort	Extensive, Familiar Product	Normal, Familiar Product	Mixed, Some Product Familiarity	Limited, Unfamiliar Product
Simple Modification, Existing Design	0.2	0.3	0.4	0.5
Extensive Modification, Existing Design	0.6	0.7	0.8	0.9
New Design, Existing Technology	0.9	1	1.1	1.2
New Design, New Product Line	1	1.2	1.4	1.6
New Design, Unfamiliar Technology	1.3	1.6	1.9	2.2
New Design, State of Art Technology	1.9	2.3	2.7	3.1

Sources: PBO and TruePlanning

Appendix D Project Schedule

Table D-1 Project Schedule

Major milestone	Date
Treasury Board Preliminary Project Approval	May 2007
Release of Definition, Engineering, Logistics and Management Support Request for Proposals	Dec 2007
DELMS RFP Close	Feb 2008
DELMS Contract Award	May 2008
Revised Project Approval (Definition) I	Oct 2011
Ancillary Contract Awarded	Jun 2012
Revised Project Approval (Definition) II	Fall 2012
Award Definition Contract	Winter 2013
Project Approval (Implementation)	2015
Award of Implementation Contract	2015
Delivery of First Ship	2018
Initial Operational Capability	2019
Full Operational Capability	2023
Project Complete	2024

Source: (National Defence and the Canadian Armed Forces, 2014a).

Appendix E Project Budget and Expenditures

Table E-1 Past and Future Government AOPS Expenditures

Original Estimated Total Cost	Revised Estimated Total Cost	Actual to Date (as of 2012-13 DPR)	Planned Spending 2012-13	Total Authorities 2012-13	Actual 2012-13
$3,073,600,000	$3,073,600,000	$52,779,000	$27,202,000	$27,202,000	$17,377,000

Source: (National Defence and the Canadian Armed Forces, 2013b).

Appendix F Risks used to determine confidence level

This table provides a summary of the parameters used to generate the confidence level for the A/OPS estimate. An explanation of the optimistic and pessimistic boundaries of these ranges is provided in the table.

Table F-1 TruePlanning Variables and their values used to determine estimate range

Variable	Optimistic	Pessimistic	Explanation of Range
Operating Specification	1.20	1.60	The default value assigned to commercial ships is 1.20 (midpoint of 1.0-1.4) whereas the default value assigned to military ships is 1.60 (midpoint of 1.4-1.8). This difference reflects the additional testing and documentation requirements associated with military when compared to commercial ships.
Weight of Structure	13,160,000 lbs (6,000 tonnes)	15,160,000 lbs (6,900 tonnes)	The selected weight range reflects the potential for variance between the ship drawings and the actual ship delivered. At the low end, the weight was selected based on fluctuations in the A/OPS specifications since it was announced. It started out as approximately 6,000 tonnes and has changed to the present 6,400 tonnes. The upper value was selected in case it increased by the same amount again.
Manufacturing Complexity for Structure	3.65	3.81	A range of complexities was included to reflect adjustments that may be made to the operational requirements of the ship. The range of values was selected using complexity values in Table 3-2. Given that all these CCGS are between 3.6 and 3.8 and that the LSL is an outlier with 4.3, a range of 3.65 to 3.81 seemed a realistic range for the A/OPS.
Engineering Complexity	1.0	1.2	Selected to account for a slightly more or less experienced development engineering team than anticipated. See section C.1 for possible values for this variable.

Source: PBO Analysis.

Appendix G Estimating CSC Construction Time

In an attempt to determine when construction would have to start on the first CSC in order for it to be delivered in 2025, a historical survey of construction times for ships similar to the CSC was carried out. The following ships were used: the Canadian Halifax class frigates, the United States Arleigh Burke class destroyers, the United States Zumwalt class destroyers, and the United States Littoral Combat Ships (LCS) Freedom class (mono hull design). The construction times for each of these ships, from the laying of the keel until they were commissioned, are shown in Table G-1 below.

Table G-1 Comparable Ship Construction Times

Ship class	Keel laid	Commissioned	Total Time
Halifax	March 1987	June 1992	5.3 years
Arleigh Burke	Dec. 1988	July 1991	2.6 years
Zumwalt	Nov. 2011	Est. 2016	~5 years
LCS Freedom	June 2005	Nov. 2008	3.4 years

Sources: (Defense Industry Daily, 2014; Wikipedia, 2014d, 2014g, 2014h)

Comparing Construction Times

Determining the time it takes to construct a ship is open to some debate. At what point is a ship considered "finished"? Are there defined criteria that need to be met before a ship is launched (clearly it has to float), commissioned, or operational? Are these criteria consistent from country to country and from ship to ship?

After a brief review, it was not clear that consistent criteria are followed for these terms. Also, depending on the complexity, it can take much longer for some ships to transition from commissioned to fully operational (assuming the same criteria are used). Notwithstanding these challenges, commissioning date was used in this report since it appeared to be the most consistent measure.

As can be seen from Table G-1, construction times vary from a low of 2.6 years to over 5 years. Assuming that the CSC wouldn't be as complex as Zumwalt and closer to the LCS and that the Irving shipyard would be experienced after A/OPS (therefore shorter duration than for the Halifax), it was assumed that the CSC would take four years from keel laying to commissioning.