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CANADA

# The Cost of Canada's Surface Combatants

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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 Canadian economy; and, upon request from a committee or parliamentarian, to estimate the financial cost of any proposal for matters over which Parliament has jurisdiction.

This report was prepared by the staff of the Parliamentary Budget Officer. Rod Story wrote the report. Peter Weltman, Mostafa Askari and Jean-Denis Frechette provided comments. Jocelyne Scrim and Nancy Beauchamp assisted with the preparation of the report for publication. Thank-you to Dr. Eric Labs of the Congressional Budget Office and one anonymous reviewer for their insightful comments. A special thank-you goes to Paul Marsden at Library and Archives Canada, who helped PBO find the Canadian Patrol Frigate Cost Performance Report that enabled this analysis. Please contact pbo-dpb@parl.gc.ca for further information.

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# Executive Summary

In June 2010, the Government of Canada announced Canada's National Shipbuilding Procurement Strategy (NSPS).[1] One set of ships within this strategy was the Canadian Surface Combatant (CSC).[2]

The CSC program is to consist of up to 15 ships to replace Canada's 12 Halifax-class frigates (also known as the Canadian Patrol Frigate or CPF) as well as three Iroquois-class destroyers.[3,4]

In 2008, the CSC program's original budget was set at $26.2 billion (then-year, or nominal, dollars): the budget is currently under review.[5] The CSC is to be built by Irving Shipbuilding Inc. at its Halifax shipyards modifying a pre-existing design from another country.[6]

The operational objective for the CSC is to replace the capabilities of both the Halifax-class and Iroquois-class ships.[7]

The objective of this report is to provide a cost estimate of the CSC program. This estimate includes costs resulting from development, production, spare parts, ammunition, training, government program management and upgrades to existing facilities. It does not include costs associated with the operation, maintenance and mid-life refurbishment of the ships, other than the spare parts that will be purchased when the ships are built.

PBO used three different cost estimation methodologies: a primary one (parametric based), as well as two secondary methodologies (heuristic based) to confirm the results of the primary methodology. The heuristic methods were based on a number of cost estimating relationships (for example, doubling lightship weight doubles cost) that the RAND Corporation had discovered in an analysis of the increasing cost for naval ships.[8]

There are two primary cost drivers for surface combatants: the ship's weight and the combat system. The weight of surface combatants has been increasing, while their combat systems have become more and more complex, both factors driving up their cost.

A lesser factor, though still material, is the cost of ammunition, specifically missiles. Canada's current naval missiles average roughly $2.3 million each. The cost to load an Iroquois destroyer averages about $115 million in today's dollars.

Summary Table 1 shows the estimated total cost of the program including costs of specific program components assuming a lightship weight (LSW) of 5,400 tons. Costs are presented in both FY2017 dollars as well as then-year dollars. For comparison purposes, the table also presents the cost of the CPF in then-year dollars. It is assumed the CSC contract is awarded in 2018 and that construction starts in 2021.

The original budget for the CSC program was $26.2 billion, or $1.7 billion per ship for 15 ships in then-year dollars. As the table shows, the estimated cost of the program in then-year dollars is $61.82 billion, or $4.1 billion per ship for 15 ships. Therefore, it is estimated the ships will cost roughly 2.4 times more than originally budgeted. It is important to note that this is a parametric point estimate using third party software. This software in tests against actual program costs has been shown to be within plus or minus 20 per cent.

### Summary Table 1 Cost estimates using parametric modelling

| | CSC cost in billions $ (FY2017 $) | CSC cost in billions $ (then-year $) | CPF cost in billions $ (then-year $) |
|---|---|---|---|
| **Total Program Cost** | 39.94 | 61.82 | 8.86 |
| **Average ship cost** | 1.66 | 2.73 | 0.47 |
| **Total development cost** | 4.53 | 5.10 | 1.03 |
| **Total production cost** | 27.82 | 45.23 | 5.99 |
| **Spares for 2 years** | 0.83 | 1.31 | 0.13 |
| **Spares for remaining years** | 4.42 | 6.96 | 0.87 |
| **Ammunition** | 0.98 | 1.54 | 0.25 |
| **Facilities** | 0.16 | 0.18 | 0.07 |
| **Documentation** | 0.07 | 0.08 | 0.03 |
| **Training** | 0.26 | 0.38 | 0.11 |
| **Government program management** | 0.88 | 1.05 | 0.38 |

Source: PBO using TruePlanning

Note: Numbers may not add up due to rounding

PBO estimates that for the program to stay within the original budget of $26.2 billion (then-year dollars), the government could build only six ships, (Summary Table 2).

Another option for reducing cost is decreasing the lightship weight (LSW) of the ship. Summary Table 3 shows that within the range of LSWs for the CSC designs under consideration, none will result in a program cost for 15 ships less than $26.2 billion. Note that the costs in the table are in FY2017 dollars rather than then-year dollars which would be higher. The CPF LSW was 3,748 long tons and the average estimated LSW of all potential CSC ship designs is about 5,200 long tons.

## Summary Table 2 CSC program cost with 6, 9, 12 and 15 ships

| | CSC cost in billions $ (FY2017 $) | CSC cost in billions $ (then-year $) | Project completion year |
|---|---|---|---|
| **Program cost for 15 ships** | 39.94 | 61.82 | 2041 |
| **Program cost for 12 ships** | 33.36 | 48.91 | 2038 |
| **Program cost for 9 ships** | 26.70 | 37.07 | 2035 |
| **Program cost for 6 ships** | 19.93 | 26.17 | 2032 |

Sources: PBO and TruePlanning

## Summary Table 3 Program cost with range of LSWs

| | CSC cost in billions $ (FY2017 $) | 1st ship cost in billions $ (FY2017 $) | 15th ship cost in billions $ (FY2017 $) |
|---|---|---|---|
| **4,200 tons** | 33.17 | 1.66 | 1.20 |
| **4,800 tons** | 36.56 | 1.89 | 1.37 |
| **5,400 tons** | 39.94 | 2.11 | 1.53 |
| **6,000 tons** | 43.32 | 2.34 | 1.69 |
| **6,600 tons** | 46.71 | 2.57 | 1.86 |

Source: PBO

PBO also estimated the cost due to inflation for delaying the awarding of the contract after 2018. We estimate that for each year of delay, the program would cost about $3 billion more.

The two heuristic methods used for validation, developed cost estimates for the ninth ship in FY2017 dollars. Ninth ships are compared because shipyards have reached the end of their learning curve at this point such that production costs are at their minimum. From Summary Table 1, the parametric model estimated the ninth ship to cost $1.59 billion in FY2017.

Using the first heuristic method, the cost of the ninth ship was estimated at $1.80 billion, while the second method produced an estimate of $1.64 billion. Both were higher than the parametric estimate, but sufficiently close to provide confidence in the parametric estimate. If anything, the parametric estimate might be too low since it might not be capturing some costs which the heuristic methods do.

PBO also estimated the cost saving of having the CSC built at the foreign shipyard that built the original ship design rather than in Canada. It was estimated that Canada would save $10.22 billion FY2017 of the total $39.94 billion FY2017 program budget, or 25 per cent.

As a final point, it should be noted that warship construction is complicated and expensive and is fraught with risk. Achieving a successful program is never easy. A RAND report summarized it well:

> *"Unfortunately, there is no magic solution to guarantee a successful program. Each new program will be different in some way and the options, decisions, and outcomes that surround a program will change. Even such countries as the United States and United Kingdom, with long histories of designing and building new classes of ships and submarines and with relatively large defense budgets, have experienced difficulties in meeting cost and schedule goals for new programs. All programs experience some bumps along the way. Successful programs anticipate them and plan for their resolution."*[9]

# 1. Introduction

The legislative mandate of the Parliamentary Budget Officer (PBO) includes providing independent analysis on the state of the nation's finances.[10] The acquisition of the Canadian Surface Combatant will be the largest single direct program expenditure for the Government of Canada in recent history.

The objective of this report is to provide a cost estimate of the Department of National Defence's (DND) Canadian Surface Combatant (CSC) program. This estimate includes costs resulting from development, production, spare parts, ammunition, training, government program management and upgrades to existing facilities.

This report explains each of these items. The estimate does not include costs associated with the operation, maintenance and mid-life refurbishment of the ships other than the spare parts that will be purchased when the ships are built.

The remainder of this report is divided into three sections. The first provides background information regarding the CSC program, surface combatants in general and important factors related to their construction. The second describes the primary estimation methodology as well as two other methodologies used to validate the results of the primary methodology. The final section outlines the results.

# 2. Background

In June 2010, the Government of Canada announced Canada's National Shipbuilding Procurement Strategy (NSPS).[11] One set of ships contained within this strategy was the Canadian Surface Combatant (CSC).[12]

The CSC program is to consist of up to 15 ships to replace Canada's 12 Halifax-class frigates (also known as the Canadian Patrol Frigate or CPF) as well as three Iroquois-class destroyers.[13,14] The destroyers have been decommissioned since the announcement of NSPS.[15]

The CSC program's original budget was set at $26.2 billion in 2008; it is currently under review.[16] The CSC is to be built by Irving Shipbuilding Inc. at its Halifax shipyards.[17]

The operational objective for the CSC is to replace the capabilities of both the Halifax-class and Iroquois-class ships.[18]

The Halifax-class frigates were designed for anti-submarine warfare (ASW), although they were also equipped with both air defence and anti-ship missiles in addition to torpedoes for attacking submarines.[19] The 12 Halifax frigates were commissioned between 1992 and 1996.[20]

The Iroquois-class destroyers were launched in the early 1970s as ASW ships, and subsequently converted into anti-air warfare (AAW) ships. This was done by adding a 32-cell vertical launch system (VLS) that is used to fire two varieties of anti-missile missiles: one for close range and one for medium range.[21] The Iroquois-class destroyers were converted from ASW to AAW ships at the same time that the Halifax-class frigates were being built.[22]

Given that the CSC is replacing both the Halifax and Iroquois, the new ships will both have ASW and AAW capabilities.

The remainder of this section discusses several topics: the frigates and destroyers; the CSC reference design; the importance of additional margin; why naval ships are so expensive; combat systems; learning curves; ammunition costs; pre-purchasing of spares; and potential risks of building another country's ship design.

## 2.1. Frigates and destroyers

The original National Defence industry engagement documents proposed that the CSC would have two variants: an ASW and AAW.[23] As noted above, this two-variant goal has been replaced by a single ship capable of both functions.[24] Nevertheless, it is useful to understand the roles of ASW and AAW ships to appreciate the mission requirements that have increased the costs of surface combatants.

Using an historical definition, the ASW variant would have been called a frigate and the AAW variant would have been called a destroyer. These definitions have been around since the Second World War.

Frigates were used as convoy escorts specializing in anti-submarine warfare. Destroyers were "multi-purpose vessels" that had light guns (between four and five inches for surface warfare), anti-aircraft guns, radar, forward-launched ASW weapons, depth-charges and torpedoes.[25]

Since WWII, the definition of what is a frigate and what is a destroyer has blurred. The best example is the ship class Alvaro de Bazan that the Spanish designate a frigate; when the Australians used the same design they designated the ship a destroyer (Hobart-class).[26]

The Alvaro de Bazan/Hobart-class of ships has a displacement of around 6,000 tonnes (full load), an Aegis combat system, AN/SPY-1D(V) radar and a 48-cell Mark 41 VLS, plus a wide variety of additional sensors and armaments.[27]

As a general rule of thumb, in 2017, a ship would be considered a destroyer if it had: a lightship weight (LSW)[28] of 7,000 tons or more; an advanced combat system incorporating either passive electronically scanned array (PESA) radar or the newer active electronically scanned array (AESA) radar; and a VLS with 48 or more cells.

As an example, the United States Arleigh Burke-Class of destroyers has an LSW of 7,000 to 8,000 tons, depending on the version, a 96-cell VLS and an Aegis combat system.[29]

### Lightship weight versus full load weight

Lightship weight (LSW) is defined as the weight of the ship without the crew, provisions, ammunition, water, fuel and oil. Full load, or deep departure, includes all these items. Shipbuilders generally publish the full load weight of their ships, but are reluctant to give the LSW since it supposedly reveals too much about a ship's capability.

Today, a ship would be considered a frigate at 5,000 tons or less (LSW), with less than a 48-cell VLS and a combat system less capable than an equivalent to Aegis AN/SPY-1D(V). As will be discussed in the next section, over half of the ship designs under consideration for the CSC straddle the line between a frigate and destroyer.

## 2.2. Possible CSC designs

On June 13, 2016, the Canadian Government announced that it would change its procurement approach from building a new design to modifying an existing design.[30] At the same time, it released a short list of companies that had qualified to bid on the design for the CSC.[31]

PBO went through the shortlist of potential shipbuilders. For each, it made a prediction about which of their existing ships they were likely to bid, as well as an estimate of each ship's LSW.[32] The results are shown in Table 2-1 below.[33]

All the predicted ships, except for the BAE Type 26 (also known as the Global Combat Ship), are currently operational in various navies. Construction of the Type 26 is scheduled to start this summer.[34] It is estimated that this first Type 26 will not be commissioned until 2023 or 2024.[35]

Note that the LSWs for the ships being considered range between 4,700 tons and 5,800 tons: four of the seven ships straddle the definition between a frigate and destroyer based on weight.

### Table 2-1 Short listed shipbuilders and their possible ships

| | **Country** | **Ship** | **Estimated LSW (tons)** |
|---|---|---|---|
| | | **Possible CSC Designs** | |
| **BAE Systems surface Ships Ltd.** | United Kingdom | Type 26 | 5,580 |
| **DCNS SA** | France | French FREMM* | 4,840 |
| **Fincantieri S.p.A.** | Italy | Italian FREMM* | 5,400 |
| **Navantia SA** | Spain | F100 | 4,840 |
| **Odense Maritime Technology** | Denmark | Iver Huitfeldt | 5,360 |
| **ThyssenKrupp Marine System GmbH** | Germany | F124/F125 | 4,680/5,800 |
| | | **Other ships for comparison** | |
| | Canada | Halifax (1992) | 3,748 |
| | Canada | Iroquois (1972) | 4,200 |
| | USA | Arleigh Burke IIA (2000) | 7,190 |
| | Australia | Hobart (2017) | 5,040 |

Sources: PBO, DND

Note: *FREMM stands for either Frégate européenne multi-mission (French) or Fregata europea multi-missione (Italian)

## 2.3. The importance of additional margin

It is important to choose a CSC design that has enough extra margin. The term margin in ship design refers to the extra capacity which a ship has with regards to weight, space and power. Extra weight margin allows for the addition of heavier items in the future without endangering the ship's stability. Extra space not only applies to a physical area that is now empty and can be filled later with a new mission system; it also applies to having the ability to run "additional cable, piping, and ducting to the impacted spaces" as well as "providing more power, cooling, or bandwidth than originally needed to the space that hold equipment and systems that have a high probability of being upgraded".[36]

As will be discussed in a later section, the ship system that will likely need to be upgraded first is the combat system. Electric power consumption of combat systems has been rapidly increasing such that if the selected CSC design does not already have the extra electric power generation capacity or the extra space to hold a larger generator, it will be extremely difficult if not impossible to upgrade the combat system in the future.

So in summary, if the selected CSC design does not have suitable weight, space and power margins, it may be extremely difficult and expensive if not impossible to modify or upgrade, potentially resulting in early retirement of the ship-class. For further information on this topic refer to the RAND report titled "Designing Adaptable Ships".[37]

## 2.4. Why are naval ships so expensive?

It is important to understand why naval ships are so expensive. A report by the RAND Corporation titled "Why Has the Cost of Navy Ships Risen?" published in 2006 provides valuable insight.[38] Its purpose was to determine why the cost of American naval ships was increasing at a much faster rate than either the Consumer Price Index or gross domestic product (GDP) inflation.

Shipbuilding inflation can be divided into two broad categories:

- Inflation incurred when building different iterations of the same ship (in-program inflation); and
- Inflation between different generations of the same type of ship (for example, a destroyer designed and built in 1972 and a destroyer designed and built in 2002).

Table 2-2 lists the inflation factors and their values. Each is explained in the remainder of this section.

### Table 2-2 Some cost inflation factors and their annual contribution for surface combatants

| | Per cent annual contribution | |
|---|---|---|
| | Between ship generation inflation | In-program inflation |
| **Characteristic Complexity (weight and power density)** | 2.1 | |
| **Standards, Regulations, and Requirements Complexity** | 2.0 | |
| **Current GDP inflation** | 2.0 | 2.0 |
| **Economy factors above GDP inflation** | 0.4 | 1.2 |

Sources: PBO, CBO and (Arena et al., 2006)

For in-program inflation, the Congressional Budget Office (CBO) in the United States has found that the cost of naval construction increases at a rate of 1.2 per cent above the GDP inflation rate.[39] This is because the basket of goods used in shipbuilding increases at a higher rate than the average of all goods and services produced by the economy. Since the early 1990s, GDP inflation in Canada has averaged 2.0 per cent.[40]

For inflation between different generations of the same ship, the RAND report found that United States surface combatants had incurred an annual inflation rate of 9.1 per cent. The report covered the 40-year period from 1965 to 2004. It also determined that two broad factors could explain 8.6 percentage points of this inflation: economy-driven factors (labour, equipment and material) and customer-driven factors (characteristic complexity, standards and requirements complexity). GDP inflation over the study time period was 4.1 per cent while currently it is only 2 per cent.

For the economy-driven factors, the report found that naval shipbuilding labour "increased at a rate greater than inflation, while material and equipment costs have increased somewhat less so."[41] Furthermore, RAND found that economy-driven factors accounted for an annual rate of increase of 0.4 percentage points higher than the GDP inflation over the same four decades.

With respect to customer-driven factors, RAND found that characteristic complexity contributed average annual increases of 2.1 per cent. Characteristic complexity is defined as "the difficulty and level of effort required to design, manufacture, integrate, and outfit a ship".[42] It is represented by proxies such as displacement, crew size and number of systems such as weapon systems. Ships have been getting bigger and their weapon systems more complex from one generation to the next.

The next customer-driven factor, standards and requirements complexity, contributed another 2 per cent. The authors described standards and requirements complexity as the non-visible requirements, such as survivability, reaction time, pollution control, radar signature, and so on.

In summary, the cost of naval ships has increased at a much higher rate than inflation (either GDP or consumer) mostly because of the increased size and complexity of the mission systems on the ships. Capability requirements of these mission systems have steadily increase as a result of the demands of fighting in increasingly complex theatres of war.

As will be discussed further in the methodology section, the RAND report found that the cost of a naval ship doubles when its LSW is doubled. The cost doubles again when its power density (measured in kilowatts of electricity generation per ton of ship) is doubled.

Power density is a proxy for the various things in the combat system for which costs have greatly increased, such as active electronically scanned array (AESA) radar and complex software. Given these metrics, it is no surprise that costs for surface combatants have been dramatically increasing; they are both getting bigger and requiring more electrical power to drive the combat systems.

## 2.5. Combat systems

From a design and costing point of view, a surface combatant is made up of seven components (also known as a Product Breakdown Structure - PBS): hull; propulsion; electricity generation and distribution; combat system[43]; auxiliary systems (for example, heating and cooling, waste treatment, etc.); outfit and furnishings, such as tables, desks, beds, kitchens and so on; and armament.

Of these, the combat system is the most expensive. The cost of the combat system for the CPF was on average about 35 per cent of the total ship cost.[44] Furthermore, as will be discussed below in the Results section, it is estimated that the combat system will average 41 per cent of the CSC’s cost.

Combat systems are expensive because they are the brains of the ship. They allow the ship both to defend itself and attack its objectives. In the continuous pursuit of naval advantage, the sophistication of combat systems has increased dramatically over the years.

Combat systems are now capable of detecting submarine periscopes, as well as tracking over a thousand objects simultaneously at distances of over a thousand kilometres in three dimensions. Furthermore, ships can now have co-operative engagement capability (CEC); that is multiple ships in a task force are networked together, sharing what each ship sees and deciding which ship will attack which threat.

Using the RAND report, PBO estimates that combat systems incur an average annual inflation rate of 6.5 per cent. (See "Appendix A: Combat system inflation" for an explanation of how the rate of 6.5 per cent was determined.) This inflation rate would be incurred between different versions of a combat system.

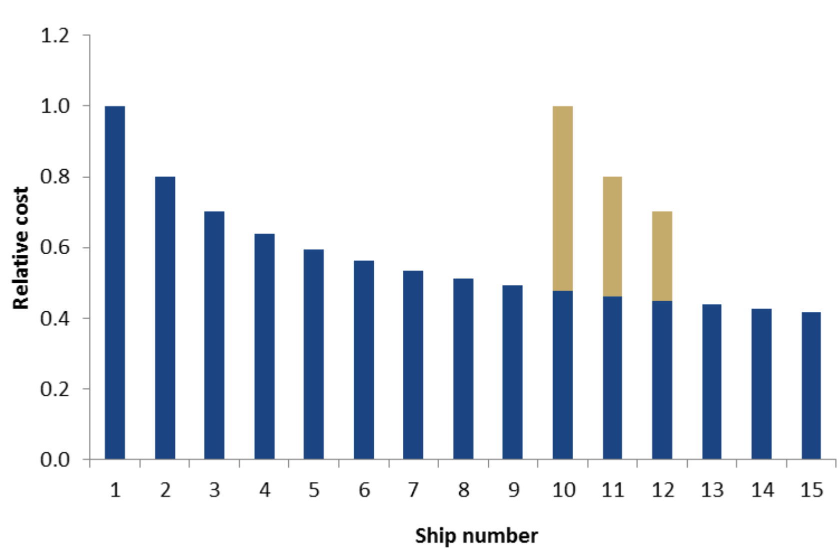
Using the CPF as an example, PBO estimated the equipment for its combat system cost $92 million in fiscal year 1991 before taxes and profit. This is a combination of government furnished equipment[45] and equipment supplied by the combat system integrator. At an annual inflation rate of 6.5 per cent, the combat system equipment would cost $473 million in 2017 (before taxes and profit).

## 2.6. Learning curves

A learning curve is used to represent the rate at which someone or something improves when repeating the same task. The first time you do a job, you will take considerably longer than the second time since you will be learning as you do it. Each time you repeat the same task you will do it faster but the improvement will become gradually smaller since there is progressively less to be learned.

Learning curves can be applied to the labour hours, material or both for a project. Typically, shipbuilding has a labour learning curve of between 80 and 85 per cent.[46] An example of an 80 per cent learning curve is shown in blue below. The parts in tan are explained later in this section.

Figure 2-1 Illustration of an 80 per cent learning curve




Source: PBO

When different shipyards have different learning curves, it is expected that the costs should be the same by about the ninth ship, with only marginal improvement after.[47] The difference between shipyards is that the cost of those first eight or nine ships will be higher at the shipyard with the steepest learning.

The nine CPF ships built by the St. John shipyard had a labour learning curve of 73%.[48] This was much steeper than typical since the shipyard was inexperienced at building surface combatants; in addition the ship design had not been completed before construction had started.[49]

Another factor that affected the CPF program was that the ships were built at two different shipyards, so the program paid for the learning curve twice: once at each shipyard. This is illustrated in Figure 2-1 by the increments added to ships 10 through 12.

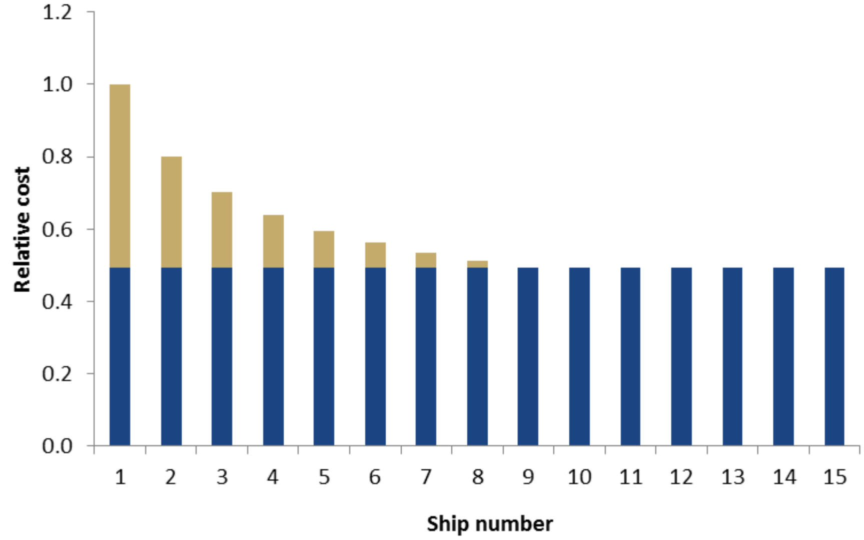
Rather than paying just the lower portion had all the ships been built in one shipyard, Canada incurred this additional cost increment. Since the CSC will be built at only the Irving Halifax shipyard, the CSC will only incur the learning curve costs once.

One last factor to recognize is the increased cost the government will incur by building the CSC in Canada. Given that the CSC will be an existing design that has already been built in another country (except for the Type 26), by building the ship in Canada, the government will be paying for the learning curve.

Using the 80 per cent learning curve shown above, the relative increase in cost by starting at number one rather than paying the cost of the ninth ship would be 16 per cent for 15 ships or 19 per cent if only 12 ships are built. The premium increases as fewer ships are constructed. The extra cost Canada will incur is shown by the tan increments in Figure 2-2.

The diagram does not show the additional cost Canada will incur when comparing costs for building a new design in Canada. Since Canada does not have experience building surface combatants, its learning curve will be steeper than for a country that has experience.[50] The first ship cost for a new design in Canada will be more expensive than the first ship cost for the same new design built in a country/shipyard with surface combatant experience.

Figure 2-2 Relative Learning curve costs by building in Canada




Source: PBO.

## 2.7. Ammunition costs

When considering the costs of surface combatants, it is important to realize that ammunition takes up a sizable portion of the budget. This is especially the case for missiles.

Currently the Halifax-class ships have 16 Evolved Sea Sparrow Missiles (ESSM) for air defence and 8 Harpoon missiles for anti-ship warfare or combat. The Iroquois-class ships have a 32-cell vertical launch system (VLS) that fires both ESSM and Standard Missile 2-Medium Range missiles (SM-2 MR).

Therefore, the Canadian navy currently uses three different missiles on its ships: ESSM, SM-2 MR and Harpoon. These missiles and their costs plus some other exemplar (though not indicative) missiles for CSC appear in Table 2-3. The text that follows examines each missile.

## Table 2-3 Possible CSC missiles, their cost and purpose

| | Use | In Canadian Navy | Estimated Cost (million $) |
|---|---|---|---|
| **ESSM** | Close range Anti-missile | Halifax and Iroquois | 2.0 |
| **SM-2 MR** | Anti-air missile and longer range anti-missile | Iroquois | 2.7 |
| **Harpoon** | Anti-ship | Halifax | 2.3 |
| **Tomahawk anti-ship** | Anti-ship* | no | 2.1 |
| **Tomahawk land attack** | Land attack** | no | 2.1 |
| **SM-6** | Anti-ballistic*** | no | 5.6 |

Sources: PBO and Wikipedia.

Notes: *Since Harpoons don't currently work in a VLS and the US is currently in the process of replacing them with missiles like this or similar, the price of a Tomahawk was used for an estimated cost.

**A stated requirement of the CSC is land attack capability. The Tomahawk was used to estimate the cost of a missile providing land attack capability.

***Currently the CSC does not have a requirement for ballistic missile defence. It is included here for illustrative purposes.

### ESSM missile

The ESSM is an anti-missile missile used by Canada, the United States and a number of other nations.[51] As described previously, both the CPF and Iroquois-class destroyers use ESSMs each of which costs roughly $2.0 million CAD.[52]

It is a relatively small missile (four are loaded into each VLS cell) and it can withstand high G-forces as it manoeuvres to take out an incoming missile.[53] Given its small size, both its minimum range (50 km) and payload (39kg) are small.[54]

### SM-2 MR missile

In addition to the ESSM, the Iroquois-class destroyers also carried SM-2 MRs. These missiles have a longer range than the ESSM (SM-2 MR's range is 74 km to 167 km) and weigh over twice as much (707 kg versus 280 kg); only one fits into each VLS cell.[55]

The SM-2 MR is considered an anti-air missile: both aircraft and anti-ship missiles.[56] It can be used for anti-ship warfare but it has both limited range and damage capability compared with the Harpoon.[57] Each SM-2 MR costs roughly $2.7 million CAD.[58]

## Harpoon missile

The Harpoon anti-ship missile is currently carried by the CPF. It requires its own launcher since it does not currently work in a Mark 41 VLS launcher.[59] It is unclear if the missile will be reused on the CSC. It would cost an estimated $2.3 million CAD in FY2017.[60]

If the Harpoon missile isn't reused on the CSC, it would need to be replaced by another anti-ship missile. One possible replacement for the Harpoon would be a new variant of the Tomahawk that launches from a VLS.[61] Other variants of Tomahawks can also be used for land attack which is another stated requirement of the CSC and isn't covered by the navy's current missile arsenal.

Assuming whatever the CSC uses for land attack and anti-ship warfare will have a similar cost to a Tomahawk, PBO estimates the current cost of each Tomahawk missile at $2.1 million CAD.[62]

Currently ballistic missile defence is not a CSC requirement. But if it was to be included, the United States ballistic defence missile is the SM-6, which is estimated at $5.6 million CAD.[63]

The above discussion is based on the United States Mk 41 VLS. The other major VLS system is the SYLVER made by DCNS of France. It is the same basic idea as the Mk 41, but comes in different configurations and takes different missiles. It does currently support the SM-2 MR, but not the ESSM.[64]

If the chosen CSC design uses a SYLVER rather than the Mk 41, it will not be possible to reuse the navy's current supply of ESSM missiles. This will represent an additional cost for the procurement. Currently each CPF has 16 ESSMs and eight Harpoons. It appears that none of the competing designs for the CSC will carry the Harpoon missile, so it is not included in this calculation.

To equip 12 frigates with 16 ESSM missiles each, the total cost would reach $384 million, or $32 million per ship.

The Iroquois destroyers had a 32-cell VLS. Assuming an equal distribution of ESSMs and SM-2 MRs, results in six cells of ESSMs (24 per ship) and 26 SM-2 MRs. Since the SM-2 MR can be used in a SYLVER VLS, only the ESSMs are considered here. To equip each destroyer with 24 ESSMs at $2 million each would cost $144 million or $48 million per ship.

These costs for the current ESSM missiles of the CPF and Iroquois do not include the additional cost for whatever spares the navy has. So if the selected CSC design has a SYLVER VLS, an estimated total of $528 million could not be reused, in addition to the cost of replacing the spares which the navy currently has in stock.

The cost of the missile load-out for a CSC depends on the missile mix it will be carrying. Since each VLS Mk 41 cell can hold four ESSMs at a cost of $2 million each, when a cell is loaded with ESSMs the cost is $8 million per cell. In contrast, other missile options in which there is only one per cell would cost between $2.1 million to $2.7 million, depending on the missile. The missile mix a CSC carries would depend on the type of mission the CSC is on.

For the sake of determining an estimate, an equal mix of all missiles was assumed. The idea is that overall the variety of possible missions and missile load-outs when taken on average would be the same as this equal mix. It is expected that the CSC will have the equivalent of somewhere between 24 and 36 Mk 41 VLS cells.

For the 24-cell case, it was assumed that four cells would contain ESSMs, 10 cells SM-2 MRs and the remaining 10 cells either land or ship attack missiles. The total cost for these missiles would then be $80 million. The 36-cell case would be 50 per cent more at $120 million.

Assuming 15 CSCs in total, the total load-out missile cost would be $1.2 billion with a 24-cell VLS and $1.8 billion with a 36-cell VLS. If the VLS was an Mk 41, this total could be reduced by $739 million (taking into account both the ESSMs and SM-2 MRs that the Halifax and Iroquois currently have).

If the CSC uses a SYLVER VLS, the saving would only be $211 million unless SYLVER VLSs can be modified to support ESSMs. These cost estimates do not include spare missiles. Note that the SYLVER VLS does not support putting four missiles in each cell. Its equivalent to the ESSM is the VT-1 of which two can be put in each VLS cell.[65]

One last point about the Mk 41 VLS is that it can currently be reloaded when dockside. Once a ship has fired all its missiles, it needs to return to port for reloading.

## 2.8. Spare parts

When acquiring ships (building or purchasing), it is necessary to acquire a supply of spare parts at the same time. Unlike cars and household appliances, there is no after-market where you can go to buy parts as you need them.

Often after the ships are built, the technology changes or the parts manufacturer is no longer in business. Certainly, it is possible to have someone custom manufacture whatever part required, but this is expensive. The cheaper alternative is to acquire the spare parts that will be needed for the life of the ship at the time the ships are built. This was done when the CPFs were built and it is assumed that the CSC will follow suit.

> *"The CPF Project acquired a lifetime buy of 30 years of repairable assemblies for ship systems (marine, electrical and hull) and 10 years of repairable assemblies for combat systems to support 12 frigates. (The combat systems buy was shorter, in recognition of a likely mid-life update.)"*[66]

Because the effectiveness of the combat system requires the latest technology for a ship literally to have a fighting chance, it needs to be replaced minimally at mid-life, if not more frequently. This explains the need for only 10 years' worth of combat system parts.

### Using an existing design: A cautionary tale - Australia's Hobart-class destroyer

National Defence has decided to build an existing surface combatant design to reduce both time and cost. Though this can be the case, it does not always work out as planned, as was discovered by Australia with its Hobart-class destroyer.

Australia selected the Spanish F100 or Alvaro de Bazan-class frigate as its design for the Hobart. Australia's motivation for selecting the F100 was the same as that of National Defence for selecting an existing design: to save time and money rather than pursuing a new design.[67]

Unfortunately, Australia has encountered numerous problems. The project is expected to be at least 15 per cent over budget ($9.2 billion AUS versus the original budget of $8.0 billion AUS) and 2 1/2 years late for the first ship (delayed from December 2014 to June 2017).[68] With the winning design selected in June 2007, it will be 10 years between design selection and commissioning of the first ship.[69]

Of the numerous problems Australia has encountered in building the Hobart, some are clearly not applicable to the CSC (multiple shipyard building the blocks and DND playing multiple roles – customer, supplier and partner).[70]

For the CSC, Irving shipyards in Halifax is the only entity building the ships, DND's only role is that of the customer; Irving is the prime contractor and it is responsible for awarding the subcontracts for the design and modifications.[71]

Nevertheless, there are three areas in which Canada has the potential to encounter problems similar to those of Australia's: underestimating the risks of the Canadian specific redesign; a shipyard with no warship construction experience; and the potential for sub-standard technology transfer from the original ship designer/builder to Irving.[72]

Underestimating the effort required to make changes to an existing warship design is not surprising when given some thought. Warships are not like ice breakers or patrol ships; they are very dense with complicated interactions among all the systems.

The word "dense" in this context refers to how jam-packed the ship is with equipment, cabling, redundancy requirements, water and smoke tight compartments, and extra layers of protection. Warships don't generally have extra space to easily add stuff, though a good ship design does provide some displacement margin to add equipment during the lifetime of the ship.

Nevertheless, the effort to make a design change to a warship is not linear: changing one item, function or feature will necessarily have multiple knock-on changes multiplying the cost and effort of the change. This is a risk that is often underestimated when making changes to the design that Canada eventually selects.

The second cost-increasing problem Canada will encounter is the lack of experience in building warships, which is not the same as building ice breakers or patrol ships. Warships are considerably more complicated to build and integrate. With this in mind, the learning curve for a shipyard that has not had previous experience building warships will be steep with a higher cost for the first unit.

As described above, this steep learning curve will result in higher construction costs (for at least the first eight ships) than those incurred by a shipyard that has previous warship construction experience.

The third area in which Canada is likely to see increased costs is the technology transfer between the original shipyard and Canada. It is difficult to capture all the nuances of building a ship through digital data files. There is organic knowledge that a shipyard develops during the construction process that is not captured in the design files.[73]

One last item is to understand the cost premium Australia is paying to build the Hobart-class ships itself.[74] For an estimated total budget of $9.2 billion AUS, Australia will acquire three destroyers at an average cost of $3.07 billion AUS each (includes all fixed costs).

In comparison, the Arleigh Burke flight IIA is 50 per cent larger than the Hobart and cost $1.9 billion in FY2010 with a 2017 delivery date.[75]

Currently, the American dollar is worth 1.33 Australian dollars. The following calculations are all in billions of dollars.

1. Convert Aleigh Burke cost to Australian: $1.9 US x 1.33 = $2.53 AUS
2. Apply US foreign military sales surcharge: $2.53 x 1.047 = $2.65 AUS
3. Multiply by three to get the average cost of three ships including all costs: $2.65 x 3 = $7.95 AUS
4. Extra Australia has paid for three ships that are two-thirds the size of the price of an Arleigh Burke: $9.2 – $7.95 = $1.25 billion AUS

Consequently, this is 16 per cent higher for three smaller ships rather than just buying an Arleigh Burke from the United States.

As the previous endnote discusses, the above comparison is to the cost of an Arleigh Burke second in the learning curve. If the comparison was to the marginal cost of the ninth ship (that is, end of learning curve), it is estimated that the Arleigh Burkes would cost $1.43 billion US each.[76] Redoing the previous calculations:

1. Convert Aleigh Burke cost to Australian: $1.43 US x 1.33 = $1.90 AUS
2. Apply US foreign military sales surcharge: $1.90 x 1.047 = $1.99 AUS
3. Multiply by three for three ships: $1.99 x 3 = $5.97 AUS
4. Extra Australia has paid for three ships that are two-thirds the size of the price of an Arleigh Burke: $9.2 – $5.97 = $3.23 billion AUS

So, using the estimated ninth ship marginal cost, Australia will pay $3.23 billion AUS, or 54 per cent, more for ships two-thirds the size.

# 3. Methodology

To estimate the cost of the CSC program, three methodologies were employed: a parametric one, plus two simpler heuristic-based ones. They were derived from two RAND reports that had investigated the cost of naval shipbuilding in the United States and Australia. The primary method was the parametric one with the two simpler heuristic-based ones used to validate its results. Each methodology will be discussed in turn.

## 3.1. Parametric estimation using PRICE software

PBO used TruePlanning® 16.0 by PRICE LLC to develop the parametric cost estimate for this report. TruePlanning is explained in the following text box.

### 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. PRICE Systems clients include the U.S. Department of Defense, Sikorsky Aircraft, NASA, BAE Systems, Gulfstream, United Technologies and Boeing.

For a full list, see: <http://www.pricesystems.com/Success/Customers>.

PBO has previously published two reports using this software. The first was in February 2013 titled Feasibility of Budget for Acquisition of Two Joint Support Ships. It provided significant detail with respect to the software and its use in developing a cost estimate. The second, dated October 2014, was titled Budget Analysis of the Acquisition of a Class of Arctic/Offshore Patrol Ships.

This current report will briefly explain the software parameters where appropriate; however, readers requiring additional information may wish to consult the earlier PBO reports or the PRICE Systems LLC website.

TruePlanning software works by first calibrating to a known program of the same type (for example, an earlier surface combatant) and then changing the parameters to reflect the new program. The theory is that past performance will inform future performance.

PRICE has compared the point cost estimates generated by TruePlanning software against a sample of final costs for completed NASA programs. The data used in configuring the TruePlanning software was only that which was known before the program was started. PRICE found that the parametric point estimate generated by TruePlanning was within plus or minus 20 per cent of the actual program cost.

To estimate the cost of the CSC program, TruePlanning was first calibrated to the CPF program using a CPF Cost Performance Report from March 31, 1994.[77] This report was from near the end of the CPF construction program; as such, the cost estimates it contained were unlikely to change significantly. The original implementation contract was awarded July 29, 1983 and the last ship was commissioned September 28, 1996.[78]

The parameters that were changed from the CPF model to create the CSC estimation were: development dates, production dates, salaries, weights of the seven work breakdown structures (the CSC is heavier than the CPF – 5,400 versus 3,748 long tons LSW), inflation rates for the various work breakdown structures, updated ammunition costs, and spare parts costs.

For the full description of modelling the CPF and CSC in TruePlanning, refer to Appendix B.

## 3.2. Heuristic estimation number 1: RAND using US data

This methodology is based on the heuristics detailed in the RAND paper "Why Has the Cost of Navy Ships Risen?".[79] The authors determined several heuristics that can be used to develop a cost estimate of a surface combatant. PBO used these heuristics to develop an alternative cost estimate for the CSC to cross-check the estimate provided by the parametric model.

The concept of the methodology is to use the paper's heuristics for the factors that increase surface combatant costs and apply them to the CPF to estimate the CSC cost. The heuristics used were:

- using the cost of the ninth ship;
- inflating by 2 per cent a year to account for non-obvious capability;
- increasing cost linearly with the increase in LSW;
- increasing cost linearly with the increase in power density;
- CBO finding of inflating at 1.2 per cent above GDP inflation when in program;
- inflating by GDP inflation plus 0.4 percentage points between programs; and
- taking into account tax rate differences between the two programs.

See Appendix C for complete details for this methodology.

The Results section contains full calculations using this methodology as well as the resulting cost estimate.

## 3.3. Heuristic estimation number 2: Cost estimation using labour cost comparisons

This methodology is based on an idea taken from chapter 5 of the RAND paper "Australia's Naval Shipbuilding Enterprise".[80] The authors compared Australia's cost performance on a variety of factors to that of other shipbuilding countries around the world. This is often referred to as "benchmarking".

PBO used the idea of the difference between United States and Canadian labour rates to convert the cost of building a ship in the United States to building it in Canada. Like the previous RAND methodology, this methodology was used for the CSC to provide another alternative estimate to validate the estimate provided by the parametric model.

Briefly, the methodology estimates the cost of building a United States ship (Arleigh Burke) in Canada by: comparing the cost of the ninth ship; using the CBO in-program inflation of the GDP inflation plus 1.2 percent; using the current United States/Canadian exchange rate; adjusting the cost for the difference in LSW; and adjusting for the difference in labour costs between the United States and Canada.

Refer to Appendix D for a complete description of this methodology.

Full calculations using this methodology and the resulting cost estimate are in the Results section, which follows.

# 4. Results

The results are divided into seven sections. They are:

- The cost estimate for the program assuming the LSW is 5,400 tons.
- A range of costs are presented based on a range of LSWs.
- The program's cost if fewer ships are built.
- The additional cost that will be incurred if a construction-start is delayed by one or two years.
- The estimated premium Canada is paying to build the ships in Canada, as well as an estimate of the amount spent to purchase goods outside the country.
- The cost estimate for the ninth ship using the first heuristic method presented in the methodology section.
- A cost estimate for the ninth ship using the second heuristic method.

## 4.1. Point cost estimates for the CSC

As previously described, an LSW of 5,400 tons was selected as the reference weight for the CSC. The construction schedule used in the model is shown in Table 4-1 and the estimated program cost is shown in Table 4-2.

The program cost estimate assumes 15 ships are built. Program costs are presented in FY2017, or real dollars, and in "then-year" or nominal dollars.[81] For reference, costs of the CPF program are included as well.

Data in Table 4-2 show the total program cost is $61.82 billion in then-year dollars. This is roughly 2.4 times more than the originally projected cost of $26.2 billion. The cost in FY2017 dollars would be $39.94 billion. The effect of the learning curve can be seen in the difference between the cost of the first and last ship: $2.11 billion for the first ship in FY2017 and $1.44 billion for the 15$^{th}$ ship.

## Table 4-1 CSC construction schedule

| | Construction start | Construction finish |
|---|---|---|
| **Ship 1** | 2021 | 2027 |
| **Ship 2** | 2023 | 2028 |
| **Ship 3** | 2025 | 2029 |
| **Ship 4** | 2026 | 2030 |
| **...** | ... | ... |
| **Ship 15** | 2037 | 2041 |

Source: PBO

## Table 4-2 Cost estimates using parametric modelling

| | CSC cost in billions $ (FY2017 $) | CSC cost in billions $ (then-year $) | CPF cost in billions $ (then-year $) |
|---|---|---|---|
| **Total Program Cost** | 39.94 | 61.82 | 8.86 |
| **9th ship cost*** | 1.59 | 2.71 | 0.39 |
| **1st ship cost*** | 2.11 | 3.41 | 0.58 |
| **Average ship cost** | 1.66 | 2.73 | 0.47 |
| **Last ship*** | 1.50** | 3.20** | 0.39*** |
| **Total development cost** | 4.53 | 5.10 | 1.03 |
| **Total production cost** | 27.82 | 45.23 | 5.99 |
| **Spares for 2 years** | 0.83 | 1.31 | 0.13 |
| **Spares for remaining years** | 4.42 | 6.96 | 0.87 |
| **Ammunition** | 0.98 | 1.54 | 0.25 |
| **Facilities** | 0.16 | 0.18 | 0.07 |
| **Documentation** | 0.07 | 0.08 | 0.03 |
| **Training** | 0.26 | 0.38 | 0.11 |
| **Government program management** | 0.88 | 1.05 | 0.38 |

Source: PBO using TruePlanning

Notes: Numbers may not add up due to rounding

*Individual ship costs are the equivalent of NATO sail away costs which include profits, taxes and 2-years of spares but not ammunition

**The 15th ship

***In the CPF case, due to the two shipyards this is the cost of the 9th ship at the St. John shipyard

## 4.2. Sensitivity of the point estimate to changes in LSW

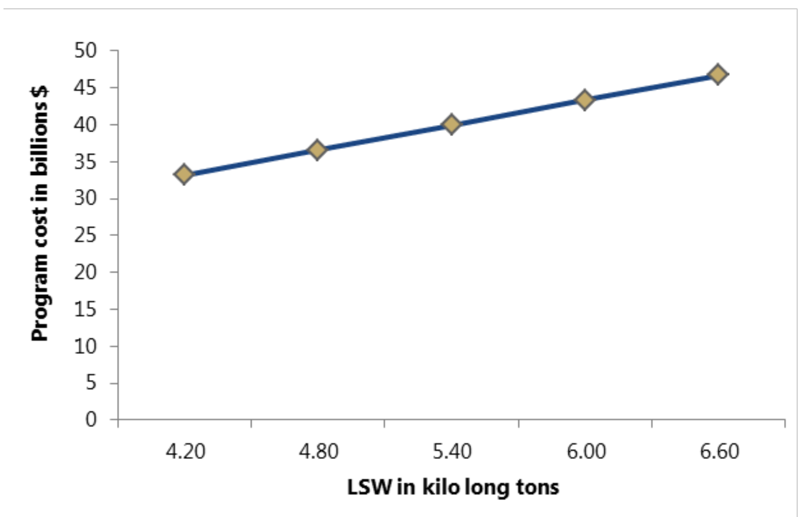
The program cost would be less expensive if the LSW of the CSC was less than 5,400 tons; conversely, it would be more expensive if it was heavier. Program costs in FY2017 dollars for a range of LSWs are shown in Table 4-3 and Figure 4-1.

Table 4-3 Program cost with range of LSWs

| | CSC cost in billions $ (FY2017 $) | 1st ship cost in billions $ (FY2017 $) | 15th ship cost in billions $ (FY2017 $) |
|---|---|---|---|
| **4,200 tons** | 33.17 | 1.66 | 1.20 |
| **4,800 tons** | 36.56 | 1.89 | 1.37 |
| **5,400 tons** | 39.94 | 2.11 | 1.53 |
| **6,000 tons** | 43.32 | 2.34 | 1.69 |
| **6,600 tons** | 46.71 | 2.57 | 1.86 |

Source: PBO

Figure 4-1 Program cost (FY2017) versus LSW




Source: PBO

## 4.3. Sensitivity of the point estimate to number of ships

As in the case of reducing the LSW, constructing fewer ships would also reduce the program cost. Cost for 15, 12, nine and six ships are shown in Table 4-4 in both FY2017 dollars and then-year dollars. Figure 4-2 graphs the CSC program cost versus number of ships in FY2017 dollars.

When fewer ships are built, the program is assumed to finish earlier in years by the number of ships removed. To build 15 ships, the completion year is 2041; to build 12, the completion date would advance to 2038, and so on.

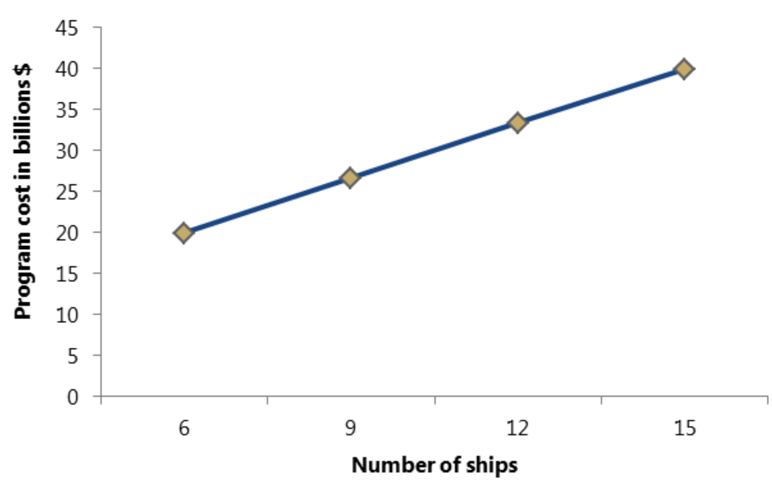
Most importantly, this analysis shows that to stay within the original then-year dollar budget of $26.2 billion, only six ships can be built.

Table 4-4 CSC program cost with 6, 9, 12 and 15 ships

| | CSC cost in billions $ (FY2017 $) | CSC cost in billions $ (then-year $) | Project completion year |
|---|---|---|---|
| **Program cost for 15 ships** | 39.94 | 61.82 | 2041 |
| **Program cost for 12 ships** | 33.36 | 48.91 | 2038 |
| **Program cost for 9 ships** | 26.70 | 37.07 | 2035 |
| **Program cost for 6 ships** | 19.93 | 26.17 | 2032 |

Sources: PBO and TruePlanning

Figure 4-2 CSC program cost versus number of ships in FY2017 dollars




Sources: PBO and TruePlanning

## 4.4. Costs of delaying CSC construction

As described above, the primary cost estimate of this report assumes a CSC start of construction (also known as production start date) of 2021. A delay would result in cost increases from two sources: inflation and a reduction in shipyard productivity.

As discussed earlier, the inflation rate for naval ships is greater than either GDP inflation or the Consumer Price Index (CPI). As Congressional Budget Office has discovered, economic inflation is 1.2 percentage points higher than GDP inflation. This affects the total cost of the ship. What has even more impact is the previously described 6.5 per cent annual inflation for the combat system. Because of these higher inflation rates, the cost of delaying is expensive.

Secondly, increased costs would occur if the Halifax shipyard completes construction of the Arctic Offshore Patrol Ships (AOPS) before the CSC starts. Based on the AOPS schedule in the earlier PBO report, if five AOPS are built, the fifth will be finished in 2022 with the CSC starting construction in 2021. This would mean an overlap of only one year. The calculations in this report assume a five year overlap.

Overlap between programs would ensure that the shipyard does not have to lay off employees and then pay for retraining new workers. Skills required at the end of construction, such as outfitting, are different than those at the start of construction, such as constructing the blocks that make up the ship (steel cutting and welding).

With an overlap of just a year, the shipyard will retain about 5 per cent of its workforce. That would necessitate an estimated 5.5 million hours of additional labour costs (due to retraining) and result in a three-year delay in the completion of the first ship.[82]

If there were no overlap (that is, if AOPS were finished and the CSC were to start in the same year or later), there would be effectively no workforce left; about six million additional labour hours would be required.[83]

Table 4-5 shows the estimated cost of the program if the program were delayed or if there was a reduced overlap. The base case would involve no delay in construction start. It assumes an overlap of about five years between the AOPS and CSC construction so that enough of the workforce is maintained to minimize additional hours because of retraining.

Say for example, that the CSC program was delayed by one year and there was an overlap of only four years. Using the data in the table, subtract the base case from the two values and then add them to get the incremental change (for example, 64.39 - 61.82 + 62.83 – 61.82 = $3.58 billion more in then-year dollars).

This simple method, however, fails to take into account the impact of inflation on the extra labour charges resulting from the reduced overlap.

**Table 4-5** CSC program cost increase if delayed

| | CSC cost in billions $ (then-year $) |
|---|---|
| **No delay and 5-year overlap** | 61.82 |
| **1-year delay** | 64.39 |
| **2-year delay** | 67.08 |
| **3-year delay** | 69.90 |
| **4-year overlap** | 62.83 |
| **3-year overlap** | 62.83 |
| **2-year overlap** | 62.99 |
| **1-year overlap** | 63.29 |
| **no overlap** | 63.42 |

Sources: PBO and (Birkler et al., 2015)

## 4.5. Building the CSC in Canada: Cost and benefits

In an earlier text box, PBO estimated the premium Australia paid by building its Hobart-class destroyers in Australia. It is possible now to calculate a similar estimate for the CSC.

In addition, a detailed parametric model has been created for the CSC. So it is also possible to determine what proportion of the ships' costs are purchased goods versus labour/material and what percentage of these purchased goods are likely to be bought in Canada.

As data in Table 4-2 show, the total cost of the program for 15 ships is $39.94 billion in FY2017. Of this total, $27.82 billion are production costs and $4.53 billion are development costs. The remaining $7.59 billion are allocated to government program management, spares, ammunition, facilities, training and documentation.

If Canada were to acquire the ships from another country (one listed in Section 2.2) without any changes, it would save the development expense, most of the government program management, and the learning curve expenses by beginning its cost at the ninth ship cost.

As Table 4-2 shows, the cost of the ninth ship in FY2017 is $1.59 billion, which includes two years of spares parts. For this calculation, first subtract the spares which cost $56 million. Then multiply by 15 and subtract the result from the total production cost.

Therefore, 27.82 - 15 * (1.59-0.056) = $4.81 billion in savings on production plus $4.53 billion on development, plus $0.88 billion on government project management, for total savings of $10.22 billion. This would be a saving of about 25 per cent on the total program cost.

Also, Canada would likely obtain the ships sooner, since the Canadian shipyard would not need the extra time to ramp up the learning curve.

Of the commercial off the shelf (COTS) [84] material that is going to be used in the CSC, there are likely to be three major components that will not come from Canada: the combat system, the propulsion system and the armament.

For the 15 ships, the combat system COTS pieces are estimated to cost $11.35 billion (including simulation system and prototype), the propulsion system COTS pieces are estimated at $1.55 billion and the armament COTS pieces, $1.19 billion. Therefore of the $32.35 billion spent on development and production, $14.09 billion or 44 per cent is likely to be bought outside Canada.

Canada will also pay increased costs since it is only building one ship per year. The number of ships built each year is known as the procurement rate. The previously described RAND report on "Why Has the Cost of Navy Ships Risen?" found that reduced procurement rates in the US has added 0.3 per cent to the annual ship cost inflation rate. When more than one ship is procured in a given year, it leads "to economies of scale in manufacturing and purchasing" which reduces the cost of building a ship. [85]

Over the 40-year period the report studied, the number of ships which the United States purchased each year has on average decreased slightly, reducing the economies of scale and resulting in this annual 0.3 per cent increase in cost.

## 4.6. Ninth ship cost using heuristic 1

The section applies the first heuristic method presented in the methodology section. The steps outlined in that section are reproduced here, but with actual values. A detailed explanation of each of the steps can be found in Appendix C.

1. From Table 4-2 above, the cost of the ninth CPF in then-year dollars is $390 million, which is assumed to be the same amount in FY1994 dollars (middle year between start and completion).
2. This step inflates by 2 per cent from 1991 to 2004 to cover for non-obvious capabilities but step 3 needs to be done first. It deflates the FY1994 value back to FY1991, the provisional delivery of the first CPS.

3. $390 million deflated from 1994 to 1991 by 3.2 per cent equals $355 million. This amount inflated by 2 per cent over 13 years equals $459 million.
4. This step increases the cost to account for the increase in weight. The LSW of the CPF was 3,748 tons and the LSW of CSC is 5,400 tons, a 44 per cent increase. Multiply 459 by 1.44 to get $661 million.
5. This step increases the cost to account for the increase in electricity density. The CPF had 1,700 kilowatts (kw) of power generation not including redundancy. Electricity used for electrical propulsion is not counted either, but the CPF did not have this. 1,700 kw / 3,748 tons = 0.454 kw/ton. The Italian FREMM has 2,800 kw of power generation not counting redundancy or electric propulsion.[86] Given that the Italian FREMM was not designed to operate in the North Atlantic during winter, add 500 kw more electricity capacity for additional heating.[87] The FREMM's electrical density is therefore 3,300 kw / 5,400 tons = 0.611 kw/ton. The increase between the CPF and the FREMM is 0.611/0.454=1.35. Multiply the cost from the previous step 661*1.35= $892 million.
6. The next step is to take into account the naval ship economic inflation over the period 1991 to 2017, which is GDP inflation plus 0.4 percentage points, which is 2.4 per cent. So inflating $892 million by 2.4 per cent for 26 years results in $1,653 million. This value is now in FY2017 dollars.
7. The last step is to add the tax difference between the CPF program which had an effective rate of 6.1 per cent and the current HST rate in Nova Scotia which is 15 per cent. So multiply $1,653 million by 1.089 to get $1,800 million for the ninth ship in FY2017 dollars.

The ninth ship cost estimate of $1,800 million is $210 million higher than the parametric estimate of $1,590 million in Table 4-2. The cost estimate for the heuristic method is 13 per cent higher, but does provide support that the parametric estimate is in the appropriate range.

## 4.7. Ninth ship cost using heuristic 2

The section applies the second heuristic method in the methodology section. The steps outlined in that section are reproduced here, but with actual values. A detailed explanation of each of the steps can be found in Appendix D.

1. The estimated cost of the ninth flight IIA Arleigh Burke at the Huntington Ingalls shipyard was $1.424 billion US in FY2014.
2. Inflating the cost by 3.2 per cent to 2017 equals $1.57 billion US.
3. Converting this value to Canadian dollars at an exchange rate of 1.33 equals $2.09 billion CAD.
4. Multiplying this value by 0.75 to account for the weight difference between Arleigh Burke and the CSC equals $1.57 billion CAD.

5. This step calculated that the Halifax shipyard wage rate is about 13.6 per cent higher than the U.S. rate after taking the exchange rate into account.
6. This final step multiplies the labour component (of step 4 to determine the final cost. Therefore, 1.57*(0.314*1.136 + 0.686) equals $1.64 billion.

This second heuristic method is only $50 million or 3 per cent higher than the parametric method giving further confidence that the parametric estimate is in the ballpark. Since both methods resulted in higher costs, it could indicate that, if anything, the parametric estimate may be slightly too low.

# Appendix A: Combat system inflation

The value of 6.5 per cent inflation was derived using results from the 2006 RAND report, while cost estimates came from the U.S. President's Budget for the Arleigh Burke (DDG51).[88] Based on the RAND report, PBO determined that two factors would influence the inflation for the combat system: economy-driven and power density.

As previously discussed, the RAND report found that economy-driven inflation was 0.4 per cent above GDP inflation. Also discussed earlier was that Canadian GDP inflation has been averaging 2 per cent since 1991 and is anticipated to continue at this rate. Therefore, economy-driven inflation is expected to contribute 2.4 per cent per year to combat system inflation.

The authors of the RAND report found that power density had increased by 88 per cent and LSW by 81 per cent over the time period in question. PBO calculated that the power density increase contributed annual inflation of 1.1 per cent to overall ship cost. This 1.1 per cent value was derived from Table 3.6 on page 39 of the report, which stated that for surface combatants the increase in LSW and power density increased the cost of ships by an average of 2.1 per cent per year.

The cost equation 3.2 on page 37 of the report was used to find the proportion of cost due to LSW weight and power density (ln Cost = 0.95ln LSW + 0.94ln PowDen). This equation was then used to apportion the 2.1 per cent between LSW and power density (that is, 1.88exp(0.94)=1.81 for power density and 1.81exp(0.95)=1.76 for LSW). Next applying the results, separate out the percentage points due to power density (i.e. (0.81/(0.76+0.81))*2.1%=1.1 per cent). Therefore, power density contributes 1.1 percent points of the 2.1 per cent.

Next it was assumed that power density is a proxy for combat systems (specifically the purchased equipment) and that the inflation of combat system purchased equipment is the cause of the 1.1 per cent annual inflation. Other than the combat system, PBO could not think of any other system on the ship that could be increasing its electricity requirements. With this assumption, it is then possible to determine the inflation rate for this equipment. This combat system inflation is over and above the economy-driven inflation.

To determine what portion of the total ship cost is combat system, the President's budget for the DDG51 (Arleigh Burke class) was used.[89] The Arleigh Burke is United States' primary surface combatant. It was assumed that everything in the electronics cost category was affected by power density and within the ordnance cost category, it would only be the Aegis weapon system.

The other items within ordnance were considered weapon system specific and have not been inflating at the same rate as the combat system. For this calculation, all dollar amounts have been left in U.S. dollars.

For this cost separation exercise, DDG 121 and 122 from FY2015 were used. Ships from FY2016 and FY2017 were avoided since they included the updated radar (AMDR). Total cost for the two ships was $2,994 million, for an average ship cost of $1,497 million each. Dividing the cost of the electronics cost category of $350 million by two gives $175 million and dividing Aegis cost of $442 million by two gives $221 million.

So, (175 + 221) / 1497 = 26.5%. Thus just over one-quarter of the ship cost is affected by power density.

Following from the assumption that power density only contributes to combat system cost, it can then be assumed that this 26.5 per cent of ship cost drives the 1.08 per cent inflation of the total ship cost. To determine the actual inflation of the combat system cost alone, divide 1.08 by 0.265 to obtain 4.1 per cent.

The final step was to add the economy-driven ship inflation from above (2.4 per cent) to obtain an overall combat inflation of 6.5 per cent.

# Appendix B: Modelling the CPF and CSC in TruePlanning

## B.1 Modelling the CPF in TruePlanning

As described above, the first step in modelling the CSC in TruePlanning was to model the CPF. Six different documents were used as data sources to create the CPF model. They are: Cost Performance Report from March 21, 1994[90]; Project Completion Report[91]; CPF PBS Data (Excel spreadsheet containing the weights of the subcomponents for each of the CPF's PBS)[92]; a one page PowerPoint chart showing "Total" Cost of Project with each cost category represented as the number of average production cost ships it represented[93]; Report on the Contract Management Framework[94]; and Report on Canadian Patrol Frigate Cost and Capability comparison[95].

Of the 12 CPFs built, three were built at the Davie shipyard in Lauzon, Quebec, while nine were built at a shipyard in St. John, N.B. During construction, the company responsible for the three ships at Lauzon encountered financial difficulties, which resulted in its receiving additional funds to complete their construction. For this reason and the previously described separate learning curve for this shipyard, only the nine ships built in New Brunswick were used to model the CPF.

Of the six documents used for CPF data, the most important was the Cost Performance Report. A considerable amount of time and energy was spent going through this report to create a detailed spreadsheet that divided all the program costs by ship number and PBS.

As described earlier, PBS stands for Product Breakdown Structure. It represents the seven basic components of a surface combatant which are: hull, propulsion, electricity generation and distribution, combat system, auxiliary systems, outfit and furnishing, and armament. Within each PBS, the costs were further separated by labour (both hours and cost), material and commercial off-the-shelf (COTS) equipment.

Material and COTS are different. Material is defined as something that can be obtained from general stores (for example steel plate, electrical cable, rivets, welding supplies, and so on). It is tracked and accounted for as it is requisitioned during the process of building each ship. COTS on the other hand includes those items specifically ordered for each ship such as the gas turbines, electric generators, pieces of the combat systems and armament.

Using data from the Cost Performance Report, it was possible to determine the labour learning curves and the material learning curves for each of the PBSs, as well as for the program as a whole. Material learning curve is like the previously described labour learning curve but applies to how much material is used. As more ships are built, progressively less and less material is wasted. TruePlanning software has material and labour learning curves as inputs for each of its cost objects.

Cost objects are the TruePlanning entities that the user assigns to each PBS. In modelling the CPF, a combination of assembly, hardware component, hardware COTS and software component cost objects were used depending on the PBS.

Data provided by the Cost Performance Report (labour cost and labour hours by firm and PBS) made it possible to determine the effective average loaded labour rate for both the shipyard as well as for the combat system integrator. Salaries were then adjusted within TruePlanning such that the overall average equalled that of the actual program.

Different salary profiles were used for the shipbuilder and combat system integrator, since the combat system integrator pay rates were found to be higher. In creating both salary profiles, the cost relationships between each of the TruePlanning resource salaries were maintained. For example, if the salary of a project manager in TruePlanning was double that of an assembler, this relationship was maintained when the salaries were adjusted.

The effective labour overhead rate was determined from page 98 of the cost performance report. That page lists the overhead for the prime contractor as $885.017 million and the total labour cost as $758.137 million. The overhead rate then works out to 116.74 per cent. This was the overhead rate for the shipbuilder. The overhead for the combat system integrator was not separated out. Given this, it was assumed that its overhead rate was the same as the shipbuilder.

Determining an overhead rate for the combat system integrator was not the only item where the cost performance report lacked enough detail. Unlike the detailed labour cost breakdown provided for the shipyard, cost data for the combat system integrator were at a much higher level. Its section of the cost performance report only provided material/COTS expense per ship, total labour hours by category for the whole program (for example, program management, quality assurance, shore facility, software, ships, etc.) and its total expenditure for each of these categories (labour and material).

An estimate of their average labour rate was determined by assuming that the software development cost was all labour (that is, no material) and by dividing its cost by its total number of hours. Assuming the software labour rate was representative for the overall combat system integrator labour rate seemed reasonable since the combat system requires highly skilled people for all its tasks.

Once there was a labour rate for the combat system integrator, it was then used to subtract out the labour costs (labour hours multiplied by labour rate) from each of the cost categories to determine the cost of any additional material/COTS. An example of additional material is the equipment required to build both the combat system prototype and the simulation facility.

In the earlier sub-section that described combat systems, the concept of government furnished equipment (GFE) was discussed. GFE presented two issues in creating the cost model for the CPF: determining its cost and determining which PBS(s) it should be assigned to.

Since GFE is supplied by the government, its cost was not included in the cost performance report. Page 46 of the project completion report contains a table that provides a high-level itemized list of the government's expenses. One of the items in the list was labelled "ship" with a cost of $589 million.

By comparing this cost to the information provided on the one-page PowerPoint slide program cost breakdown, it was decided this was most likely the GFE. This then equates to $49 million per ship. This value for GFE is in the same range as the value presented on page 15/48 of Report on the Contract Management Framework[96] ($0.47 billion).

The next issue was deciding how much of the GFE should be apportioned to the combat system PBS versus the armament PBS. It was assumed that GFE encompasses both these PBSs because it would likely include both classified combat system items such as sensors (radar, for example) and classified armament items such as missile systems.

Without any prior knowledge on how to separate the costs, it was decided to assign the amount using the ratio of combat system cost to armament cost of that of an Arleigh Burke. Using the costs of DDG 119 from FY2014, it was determined that 78 percent of the combined combat system and armament costs are combat system and 22 per cent are armament. Taking the $49 million per ship value from above resulted in $38 million GFE added cost to the combat system and $11 million added cost to armament.

When the CPF project was started, Canada had a Manufactures Sales Tax (MST) instead of a Goods and Services Tax (GST). The MST was replaced by the GST in January 1991, which was part way through the CPF project.[97] Since there wasn't a consistent tax rate in place throughout the program, the effective tax rate for the program was estimated from the project completion report.[98]

On page 45, the project completion report lists a total of $323 million in Federal Sales Tax (FST) which is another name for the MST or GST. The effective tax rate was then determined by dividing the $323 million by the total contractor ceiling price of $5,299 million (on page 45 as well) which results in a tax rate of 6.1 per cent.[99]

The estimated profit rate for the program was estimated in a similar way to that of the tax rate. On page 40 of the project completion report, the prime contractor's total budget before profit was listed as $3,070 million and the prime contractor's profit was $401 million. On page 98 of the cost performance report the combat system integrator's total budget before profit was given as $1,926 million, along with a profit of $138 million. The effective profit rate of 11 per cent was determined by dividing the sum of these two profits by the sum of the total budgets before profits.

With the above calculations complete, it was then possible to model the CPF PBS in TruePlanning software. The modelling process followed a sequence of 11 steps.

1. For each PBS it was determined if it should consist of only a COTS object (when there was very little other material that is propulsion, combat system, auxiliary systems and armament) or a COTS object and a hardware object, such as hull, electric and outfit and furnishing. The combat system was also assigned a software development cost object.
2. Each of the COTS components was assigned a cost that was derived from the cost performance report. The number of lines of software was adjusted into order to match the software development cost in the cost performance report. The resultant number of lines of software matched the number lines of software that were actually written[100] providing confidence in both the estimated labour rates and the TruePlanning modelling software.
3. The learning curves values for the both labour and material that had been calculated for each PBS were entered.
4. The weights for each PBS were obtained from the previously described Excel spreadsheet of weights obtained from DND. When weights were available for COTS components from this spreadsheet they were used. Otherwise, a weight was assigned based on its percentage of cost of its PBS.
5. The various dates for the project such as development start and finish as well as production start and finish dates, were entered. The model allows the total percentage of all ships that were completed in any given year. This means that if in a given year 20 per cent of ship one was completed and 10 per cent of ship number two was completed and no other ships were worked on, 0.3 would be entered. This signifies that 0.3 out of a possible 12 was completed. All dates were obtained from the project completion report.
6. Labour rates and overhead as described above were entered.
7. TruePlanning software has the concept of Manufacturing Complexity of Structure (MCS) which represents the level of technology in a component as well as its production difficulty. The combat system

therefore, has a much higher MSC than the hull. MCS was adjusted so that the average unit cost for the PBS matched the actual unit cost as estimated using the cost performance report.

8. The modelling software also has the concept of Manufacturing Process Index (MPI). MPI is used to determine the cost of the first piece that is generated. It is influenced by the level of manufacturing process maturity and the degree of automation. With respect to ships, the level of automation is very low. MPI works in conjunction with learning curves to determine both an individual unit's cost as well as the overall average unit cost. In most instances, the MPI automatically assigned by TruePlanning was used. In two instances, this automatically assigned MPI was too low (hull and propulsion). MPIs that were assigned manually were more in line with MPIs for other surface combatant hulls and propulsion.
9. At this point, the model for each PBS assigned too much material and too little labour when compared to the actuals from the cost performance report. This was then adjusted by setting the "Material Index for Production Manufacturing", which allows the cost modeller to either move material cost to labour or labour to material. In this case, material cost was moved to labour cost.
10. The final step was to adjust the overall production and development labour hours. Even after adjusting the MPI in step 9, the model still assigned too many hours to development and not enough hours to production. This was corrected by using the TruePlanning's resource multipliers to increase all production resources and decrease all development resources. Note that the labour hours and costs incurred by the two design firms, J. J. McMullen Associates and Versatile Vickers System Inc., were included in the total development hours.
11. The last items to be added were the profit rate (11 per cent) and tax rate (6.1 per cent) based on the calculations described above.

Once the CPF had been modelled in TruePlanning, there were two remaining items that needed to be included in the overall model: spares and ammunition; and other government supplied pieces. Each will be discussed in turn.

An estimated value for spares and ammunition was determined by using the government specific cost data from page 46 of the CPF project completion report[101] and the one page PowerPoint slide which showed total cost divided into ships.

Comparing these two sources enabled the determination that the "material support" line item of $1.253 billion was for spares and ammunition. Furthermore, based on the one page PowerPoint slide, $253 million was assigned to ammunition and $1 billion was assign to spares. This value for spares is very close to the value presented on page 15/48 of Report on the Contract Management Framework[102] ($0.97 billion).

The earlier sub-section on "spares parts" stated that the sparing regime for the CPF was 10 years of combat system spares and 30-years' worth for other ship systems. To compare total ship procurement costs between countries, the NATO sail-away cost standard was used.[103] The standard states, among other things, that the ship cost should include initial spares. PBO determined this to be two years' worth of spares.

Furthermore, it was assumed that the value of combat system spares and that of the other ship systems were the same even though they were for different time periods. This was thought to be a reasonable assumption since, as noted earlier, combat systems are much more expensive than other ship systems. The following are the calculations for the cost of spares for two years (initial supply).

1. Divide $1 billion by two to get combat system and other ship systems portions. $1 billion / 2 = $500 million each.
2. Since the $500 million for combat systems is for 10 years, divide this number by five to get two years' worth. $500 million / 5 = $100 million for two years of combat system spares for the 12 CPF.
3. To get individual ship cost for 2-years of combat system spares, divide by 12. $100 million / 12 = $8.3 million
4. For the other ship system spares for two years, take the $500 million and divide by 15. $500 million / 15 = $33.3 million for all 12 ships.
5. To get individual ship cost for two years of other ship system spares, divide by 12. $33.3 million / 12 = $2.8 million
6. Add the two sets of numbers to get the total cost of spares for two years. $8.3 million + $2.8 million = $11.1 million.

To get the cost of the spares beyond two years, simply divide the starting value of $1 billion by 12 and subtract the two-year total of $11.1 million.

($1,000 million / 12) - $11.1 million = $72.2 million cost of spares beyond two years for each CPF.

The cost of spares for two years and the cost of spares beyond two years were modelled as two separate cost objects in TruePlanning to ease ship cost comparisons with other countries using the NATO standard.

The ammunition cost per ship was determined by dividing the total cost of ammunition from above ($253 million) by 12 to get $21.1 million per ship. Ammunition is not included in sail-away costs.[104] Ammunition was modelled as a separate cost object in TruePlanning.

The final four government items (project management, facilities, training and documentation) were modelled using four separate purchased good objects. Their costs were obtained from the same table as the GFE, spares and ammunition (page 46 of the project completion report).

Since their costs were in "then-year"[105] dollars, the purchase date that was entered into the model for them was based on an estimate of the middle point of the time period over which they were thought to have been purchased.

Facilities and documentation were treated as one-time purchases such that they were not assumed to have recurring costs for each ship. Facilities were $69.6 million and documentation was $32.9 million.

Training and government project management were both divided into two portions: fixed cost and variable cost. For training, the fixed cost was the effort to create the entire course material and the variable cost was the incremental effort to train each of the ship crews. For government program management, the fixed cost was for the design and production start-up, while the variable cost was the program management required to build each ship.

Without any data by which to separate the fixed and variable costs, it was decided to simply divide the total cost for each item in two and assign half to the fixed costs and divide the remaining cost equally between the 12 ships. For training, this resulted in $54.5 million being assigned to fixed costs and $4.5 million to each ship in variable costs. For government program management it resulted in $191 million of fixed costs and $15.9 million in variable costs per ship.

With all the above data entered in the model, the model matched the costs (both labour and material) and the development/production timeline of the CPF program for the nine ships built in New Brunswick. With the CPF modelled in TruePlanning, it was then possible to model the CSC program. It is discussed in the next section.

## B.2 Modelling the CSC in TruePlanning

With the CPF modelled in TruePlanning, the next step was to change those parameters that were different for the CSC as follows:

1. Change the weight of each PBS to account for the heavier CSC.
2. Change the number of ships to be built.
3. Change the various dates for the program, such as development start and production start as well as the dates for the government activities such as training, spares, facilities and documentation.
4. Change some of the learning curves.
5. Update the salaries to reflect the current wage rates.
6. Input inflation rates for each cost object.
7. Change the tax rate.

8. Update cost of spares: both combat system and other systems.
9. Missile costs.

Each of the above items will be discussed in turn.

The selected LSW for the CSC was the Italian FREMM's (Table 2-1) at 5,400 long tons. This is by no means to recommend this ship-class. It was selected purely to model the weight of an existing ship that was lighter than the Type 26, Arleigh Burke and DND's 2014 concept ship (5,654 tons LSW) but heavier than the French FREMM, F100, Iver Huitfeldt and the F125/125. This LSW was used only as a reference point. In the results section the costs for ships weighing between 4,000 and 7,000 long tons are presented.

The default number of ships was entered as 15 to represent replacing the 12 Halifax-class frigates and three Iroquois destroyers.

For program dates, development was scheduled to start in the middle of 2018 and end by the middle of 2023. Production was set to start in the middle of 2021 with the 15$^{th}$ ship being delivered in 2041. For items like the building of facilities and the development of the documentation, they were assumed to start in 2021 and be completed by 2025.

Government program management was divided into a development portion (2018-2025, the biggest expense) and a production portion for each of the ships (2021-2041). Spares and ammunition were bought two years before the commissioning of each ship (2025-2039). Development of the training program was assumed to run between 2023 and 2025 with the actual training starting in 2025 and finishing with the last ship in 2041.

When starting to build a modified ship-class at a shipyard for the first time, it is recommended that construction on the second ship of the class does not start until two to three years after the first ship; construction would start on the third ship one to two years after the second. After the third ship, a ship can be started every year.

The purpose of staggering the start of the first three ships is to allow for resolving problems that will occur when building a modified design before starting the second and third ship. It is anticipated that the first ship will take six years to build; this would drop to four years by the fourth or fifth ship.[106]

As mentioned earlier, the overall labour learning curve for the CPF was 73 per cent and a typical surface combatant learning curve is between 80 and 85 per cent. Furthermore, for the CPF TruePlanning model, separate labour and material learning curve values were entered for each of the cost objects.

Since the Halifax shipyard, where the CSC is to be built, will have had experience building the Arctic Offshore Patrol Ship (AOPS), all learning curve values below 80 per cent were changed to 80 per cent to reflect this experience.

In addition to changing the learning curve, if the TruePlanning manufacturing process index (MPI) for the cost object was too high for the new learning curve value, it was lowered. The lowering of the MPI value reduces the cost of the first item constructed thereby reducing the overall production cost.

The next item changed in the model was updating the wage rates to the ones currently being paid at the Halifax shipyard. PBO found a copy of the current collective agreement for the Halifax shipyard on the Internet. It was used to update the wage rates in TruePlanning.[107]

Since the shipyard wage rates were only for construction of the ship and not the combat system, they were used only to change the wage rates specific to shipbuilding. The wage rates in the collective agreement were all for the equivalent of TruePlanning's Fabricator/Assembler resources. As was done for the CPF, all other TruePlanning resource wage rates were then changed while keeping the same ratios between them and the Fabricator/Assembler resource.

Remaining consistent with the CPF program, it was assumed that the combat system resources for the CSC would be paid more. Therefore, a design engineer working for the shipyard gets paid less than a design engineer working for the combat system integrator. Since the combat system will come from outside the country, it was decided that the default wage rates that came with TruePlanning would best reflect this.

The sixth item that needed to be changed in the model was the inflation/escalation rates both between the CPF and CSC programs and during the construction of the CSC. Between the CPF and CSC programs and during the program, GDP inflation plus 1.2 per cent was used for the development and production of the ships reflecting the previously discussed findings of the CBO.[108]

All government functions such as facilities, training, documentation and program management used only GDP inflation. Lastly, as discussed in the subsection on the combat system, it was inflated by 6.5 per cent between the first CPF and the production start of the first CSC. After production start, the combat system was inflated at GDP inflation plus 1.2 per cent (see Section 2.5 and Appendix A).

The seventh item is changing the tax rate. As discussed in the modeling of the CPF program, its effective tax rate was 6.1 per cent. This was changed to 15 per cent, which is the current HST rate in Nova Scotia.[109]

The second last item that needed changing in the model for the CSC was the cost of the combat system spares. Since the combat system is increasing at a higher rate than the rest of the ship components, its spares needed to be treated differently than just applying GDP inflation plus 1.2 per cent. This was done by keeping the same CPF ratio of the cost of combat system spares to total combat system COTS costs.

For consistency, the CPF ratio for other ship system spares was maintained as well. This resulted in two years of spares at a cost of $54.7 million per ship ($47.7 million for combat system and $7.0 million for other systems). For the spares beyond two years, (two to 10 years for combat system and two to 30 years for other systems) it resulted in $290 million per ship ($191 million for combat systems and $98.6 million for other systems) in FY2017 dollars.

The last item that needed changing for the CSC model was the ammunition costs. Following from the discussion in Section 2.7 on Ammunition costs, assuming a 24-cell Mk 41 VLS the missile cost would be $80 million. From discussions with DND, a 24-cell Mk 41 VLS is the equivalent of a 36-cell SYLVER (since SYLVER cannot quad-pack missiles – see Section 2.7 making the missile load-out costs close enough to use the same costs for both.

Given that the SYLVER does not currently support ESSMs, only the cost of the existing SM-2 MR missiles was deducted from the $80 million ($80 million - $211 million/15) for a total of $66 million per ship for missiles. This total does not include the cost of any spares.

Obviously many parameters were left unchanged when the model was modified to derive a cost estimate for the CSC. Nevertheless, it is important to note that the software development effort was left the same. It wasn't increased or decreased.

Even though the CSC is buying an existing design, including the combat system, it was felt that some of the design modifications that would be made would involve some combat mission systems. This would then require modifications to the software. It was thought that the relative small size of the CPF software in comparison to more modern combat systems would approximate the amount of changes required.

# Appendix C: First heuristic estimation

As described in the main text, this methodology is based on the heuristics detailed in the RAND paper "Why Has the Cost of Navy Ships Risen?". Since the paper and its findings/heuristics were discussed in detail in Section 2.4 earlier, only those heuristics used for costing the CSC are explained here.

A total of four heuristics and one finding from the paper were used in combination with a Congressional Budget Office (CBO) finding and a PBO finding to create this alternative cost estimate. Each is discussed below.

1. The finding from the paper is that using the cost of the ninth ship allows for more accurate cost comparisons. In general, by the ninth ship, the shipyard has finished going through the steeper part of the learning curve and further cost improvements are much smaller. So, comparing ninth ships is more accurate since the near minimum costs for both shipyards have been reached.
2. The first heuristic is that 2 percentage points of the annual increase in ship cost is attributable to non-obvious capability growth such as survivability, reaction time, reliability and maintainability, endurance, habitability, radar and noise signatures, and regulations. This cost increase occurs in the period of time between the delivery of the first ships in class. The first CPF was provisionally delivered in 1991; for the purpose of this estimate, the first CSC is considered to be delivered in 2017. The paper's dataset only covered until 2004 and it is uncertain if this increase continued after. To be conservative in the analysis, the 2 per cent inflation was only used from 1991 to 2004.
3. At this point, the CBO heuristic gets used. Since it is necessary to compare the cost of the ninth ships while at the same inflating costs between first ship deliveries, it is then necessary to deflate the cost of the ninth from the year it was delivered to the year the first ship was delivered. This is where the previously discussed CBO in-program inflation, which is GDP inflation plus 1.2 per cent, gets used. So for the CPF, the ninth ship of the St. John shipyard, which was delivered in 1996, needed to be deflated back to 1991. A rate of 3.2 per cent was used.
4. The second heuristic is that the cost of the ship increases linearly with the increase in LSW. Another way of putting this is that if the LSW of the ship doubles, the cost doubles.
5. The third heuristic has the same effect of the previous one but deals with power density. As previously described, power density is measured in kilowatts per ton and is a proxy for the increasing complexity of combat systems. As the sophistication of radars, sensors and weapon systems increases, so does the electrical power need of the ship. As power generation per ton doubles, so does the cost. As an aside, doubling both the LSW and power density would quadruple the cost.

6. The fourth heuristic is to inflate the cost of the ship between programs by GDP inflation plus 0.4 per cent, in this case from 1991 to 2017.
7. The last item is to account for the tax differences between the two programs which is a PBO specific requirement. As discussed earlier, the effective tax rate for the CPF program was 6.1 per cent and the HST tax rate in Nova Scotia is currently 15 per cent. The difference between the two is 8.9 per cent. Therefore, the cost needs to be multiplied by 1.089 to account for this.

# Appendix D: Second heuristic estimation

As previously described in the main text, this methodology is based on an idea taken from chapter 5 of the RAND paper "Australia's Naval Shipbuilding Enterprise", which used the concept of benchmarking. PBO used the idea of the difference between U.S. and Canadian labour rates to convert the cost of building a ship in the United States to being built in Canada.

The full methodology is outlined below.

1. Like the previously described RAND methodology, it is necessary to use the cost of the ninth ship. In this case an estimate of the ninth Arleigh Burke built at the Huntington Ingalls shipyard was used. The estimate used the restart of the flight IIA with the contract awarded in FY2010 (DDG 113 – ship number one of the restart) and FY2014 (DDG 119 – ship number four of the restart at the shipyard).[110] Conveniently in those two years, only one contract was awarded and each contract was for the Huntington Ingalls shipyard. The DDG 113 price was inflated to FY2014 using the previously described CBO in-program inflation rate of GDP inflation plus 1.2 per cent (therefore 3.2 per cent). Then a learning curve was fit to these two points from which an estimated cost for the ninth ship could be determined. This resulted in a cost of the ninth ship in FY2014.
2. Since the cost comparison is being made in 2017, the estimated cost of the ninth ship is inflated by the previously described 3.2 per cent in-program inflation from 2014 to 2017.
3. Convert the ship cost from US currency to Canadian. An exchange rate of 1.33 was used.
4. From the previous methodology, scale the cost of Arleigh Burke by the weight of the hypothetical CSC. The LSW of the Arleigh Burke flight IIA is 7,190 tons and that of the hypothetical CSC is 5,400 tons. So multiply the cost from step three by 5,400/7,190 or 0.75.
5. The next step is to take into account the labour cost difference between the United States and Canada. This was accomplished by comparing the cost of ship welders in the two nations. According to the U.S. Bureau of Labor Statistics, the mean hourly wage for ship welders (specifically SOC code 514120 – welding, soldering and brazing workers in ship and boat building) in May 2016 was $22.36 US.[111] The wage for welders at the Halifax shipyard in 2016 was $33.79 CAD.[112] When using an exchange rate of 1.33, the Halifax shipyard welders are 13.6 per cent more expensive than their American counterparts (33.79/(22.36x1.33). If the Canadian dollar depreciates with respect to the U.S. dollar, this wage premium will diminish; conversely, it will increase if the Canadian dollar appreciates with respect to the greenback.

6. From the PBO parametric model for the CSC, it was determined that 31.4 per cent of the cost of the ninth ship is labour. With this knowledge, inflate 31.4 per cent of the ship cost from step four by 13.6 per cent to account for the labour cost difference. Add this back to the 68.6 per cent of the ship cost to get the final ship cost.

There are two assumptions with the above methodology. First, it assumes that the labour efficiency is the same between the US and Canadian shipyard. After building nine CSCs and building the AOPS before that, this might not be an unreasonable assumption.

Second, in scaling the cost of the Arleigh Burke only by weight, it assumes that the electrical density, as described in the previous methodology, is the same. This was thought to be a reasonable assumption, given that the CSC will have a modern combat system and that an Arleigh Burke flight IIA was used for the comparison, not the latest flight III version.[113]

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# Notes

1. National Defence (2010)
2. Public Services and Procurement Canada (2016)
3. Ibid. National Defence and the Canadian Armed Forces (2017). There were originally four destroyers built in the early 70s, but one was mothballed in 2000 and decommissioned in 2005. Wikipedia (2017l). Two other destroyers were decommissioned in the fall of 2014 and the last one was decommissioned in March 2017. Wikipedia (2017n)
4. The term "class" refers to all the ships built using "essentially" the same design. Often there are changes to both the hull (generally length) and systems of a ship and it will keep the same class name. The name given to a class of ships is the name of the first ship built using the design.
5. National Defence and the Canadian Armed Forces (2017), Public Services and Procurement Canada (2016)
6. Government of Canada (2016b)
7. National Defence and the Canadian Armed Forces (2017)
8. See Arena, et al. (2006)
9. Schank, et al. (2014, p. 3)
10. Parliament of Canada Act (2007), Arena, et al. (2006)
11. National Defence (2010)
12. Public Services and Procurement Canada (2016)
13. See supra note 3.
14. See supra note 4.
15. Wikipedia (2017n)
16. National Defence and the Canadian Armed Forces (2017), Public Services and Procurement Canada (2016)
17. National Defence and the Canadian Armed Forces (2017)
18. Ibid.
19. Wikipedia (2017j)
20. Ibid.
21. Wikipedia (2017n)
22. Wikipedia (2017j)
23. Carosielli (2014)

24. Government of Canada (2016b)
25. Wikipedia (2017g), Wikipedia (2017e)
26. Wikipedia (2017b)
27. Wikipedia (2017m), Wikipedia (2017b)
28. Lightship weight refers to the displacement of the ship without fuel, sailors, supplies or ammunition.
29. The Aegis combat system can have either PESA or newer AESA radar depending on the version.
30. Government of Canada (2016b)
31. Government of Canada (2016a)
32. LSW is important in determining a ships construction cost as will be explained in the methodology section.
33. Government of Canada (2016a), Wikipedia sites for each of the ships and PBO calculations. To convert from full load weights to LSWs, the full load weight was multiplied by 0.82 which is the ratio for the CPF for which PBO had the actual data.
34. Wikipedia (2017h)
35. PBO calculations based on Birkler, et al. (2015)
36. Schank, et al. (2016, p. 19)
37. Ibid.
38. Arena, et al. (2006)
39. Congressional Budget Office (2017)
40. PBO calculation using Statistics Canada CANSIM table 380-0064 Gross domestic product, expenditure-based.
41. Arena, et al. (2006, p. 30)
42. Ibid. p. 33
43. For this report, combat system includes both command and surveillance (radar, other sensors (e.g. ASW sensors, communications) and the ability to control the various weapon systems (both defensive and attack) but not the actual weapons themselves which is considered armament.
44. Only considering the nine CPF ships built in the St. John shipyard, PBO estimated that the average ship cost including profit, taxes and spare parts for two years but not ammunition was $457 million in "as spent" dollars. The average cost of the combat system (CPF knew it as command and surveillance) including labour, purchased equipment and material is estimated to be $160 million.
45. Government furnished equipment is equipment that due to foreign military sales restrictions can only be sold government to government and not directly to the shipbuilder/system integrator. Most of the combat system falls into this category.
46. Mislick and Nussbaum (2015)

47. See Arena, et al. (2006) where the authors performed a regression analysis indicating ship costs stabilize by the ninth ship.
48. PBO calculation using data from a CPF cost performance report (see Prime Contractors for CPF Program (1994))
49. National Defence (2005)
50. Birkler, et al. (2015)
51. Wikipedia (2017p)
52. The price for ESSMs can be found here: Department of the Navy (2016b) ($1.43 million). An exchange rate of 1.33 was used to convert to Canadian dollars. It is assumed that the foreign military sales surcharge of 4.7 per cent would apply as well. See Defense Security Cooperation Agency (2014).
53. Department of the Navy (2016b)
54. Wikipedia (2017p)
55. Wikipedia (2017o)
56. Ibid.
57. Wikipedia (2017c)
58. PBO estimated cost based on US navy cost from FY2008 budget ($2.13 million) inflated to FY2017 at 2 per cent per year and converted to Canadian dollars using a 1.33 exchange rate plus multiplying it by 1.047 for the US foreign military sales surcharge (see supra note 52). See Department of the Navy (2007).
59. Wikipedia (2017k)
60. PBO estimated cost based on US navy cost from FY1996 budget ($1.1 million US) inflated to FY2017 at 2 per cent per year and converted to Canadian dollars using a 1.33 exchange rate plus multiplied by 1.047 for the US foreign military sales surcharge (see supra note 52). PBO had to use data from the mid-1990s since the US navy appears not to have purchased Harpoon missiles since that time. See Department of the Navy (1996).
61. Wikipedia (2017a)
62. In the US Navy FY2017 procurement budget, Tomahawk missiles cost $1.5 million US each (see Department of the Navy (2016b)). Multiply this by the 1.047 for the US foreign military sales surcharge (see supra note 52) and the 1.33 exchange rate resulting in $2.1 million CAD.
63. The SM-6 cost $1.5 million US in FY2017. Multiply this by 1.33 for the exchange rate and by 1.047 for the foreign military sales surcharge. See supra note 52 and ibid.
64. DCNS (2014)
65. Wikipedia (2017d) and DCNS (2014)
66. National Defence (2005, p. 22)
67. Wikipedia (2017m)
68. Ibid.

69. Ibid.
70. Ibid.
71. National Defence and the Canadian Armed Forces (2017)
72. Wikipedia (2017m)
73. PBO personal communications and ibid.
74. The analysis provided here is based on an earlier analysis performed by the Australian Strategic Policy Institute. See Davies, et al. (2012)
75. The Arleigh Burke used in this example is DDG116 and was the second ship built by Bath Iron Works after the US restarted building Arleigh Burkes. Since the US had stopped building Arleigh Burkes, the two shipyards that build them had to go through the learning curve again. So the cost comparison to the average cost of the first three ships of the Hobart-class is valid.
76. Cost estimate of the ninth Arleigh Burke at each of the US shipyards estimated by PBO using cost data from the Department of the Navy (2016a)
77. See Prime Contractors for CPF Program (1994)
78. National Defence (2005)
79. Arena, et al. (2006)
80. Birkler, et al. (2015)
81. FY2017 or real dollars means the costs expressed in terms of all the money being spent in 2017. All costs have been deflated (using the various inflation values described in the report) back to 2017. "Then-year" or nominal dollars is the cost totaled based on the cost of the item when the money is actually spent. Given that cost inflates over time, FY2017 or real dollar costs are necessarily less than then-year or nominal dollars.
82. All the data for this analysis comes from Birkler, et al. (2015) which analysed almost the exact same issue for the gap between the end of construction of Australia's Hobart class destroyer and the start of their new frigates. Note that Figure 4.4 of their paper shows minimum unproductive hours of approximately 3 million hours which is due to normal attrition (from discussion with the authors). These 3 million hours have been subtracted from all PBO calculations since they are already built into the cost model.
83. PBO estimation based on ibid.
84. When COTS is used in military applications, it is often referred to as MOTS where the "C" has been replaced by an "M" for military. This distinction is not being made in this report such that the term COTS is used for all purchased equipment even it is only used for military applications.
85. Arena, et al. (2006)
86. Wikipedia (2017f)
87. PBO sources.
88. Arena, et al. (2006), Department of the Navy (2016a)
89. Department of the Navy (2016a)

90. Prime Contractors for CPF Program (1994)
91. National Defence (2005)
92. This was obtained from DND.
93. This can be found in Library and Archives Canada DND files for the CPF.
94. Interdepartmental Review of the Canadian Patrol Frigate Project (1999)
95. Chief Review Services (1999)
96. Interdepartmental Review of the Canadian Patrol Frigate Project (1999)
97. Makarenko (2007)
98. National Defence (2005)
99. The manufacture's sales tax was 13.5 per cent, so obtaining an effective rate of only 6.1 per cent means that the manufacture's tax was charged on only a portion of the total contract price. See Wikipedia (2017i)
100. See National Defence (2005)
101. Ibid. p. 68
102. Interdepartmental Review of the Canadian Patrol Frigate Project (1999)
103. Chief Review Services (1999)
104. PBO sources.
105. "then-year" is a financial term that means the cost reflects the money as it is spent including the effects of inflation (also known as nominal, current year or as-spent dollars). For example if $1.00 was spent last year and $1.10 this year, the total as a "then-year" value would be $2.10. The counterpart to "then-year" is constant year which adjusts for inflation (also known as real, constant year or base-year dollars). Using the previous example with 10 per cent inflation, the value of the two years in the first year would be $2.00 since the $1.10 of the second year is reduced by $0.10 to remove the 10 per cent inflation.
106. The scheduling and build times suggested in this paragraph have come from PBO analysis of the CPF schedule, Arleigh Burke schedule (see Department of the Navy (2016a), and Birkler, et al. (2015)).
107. Halifax Shipyard Collective Agreement 2012-2017 (2013)
108. Congressional Budget Office (2017)
109. Wikipedia (2017q)
110. Department of the Navy (2016a)
111. United States Department of Labor Statistics (2017)
112. Halifax Shipyard Collective Agreement 2012-2017 (2013)
113. Flight III Arleigh Burke's have AESA (Active Electronically Scanned Array) or also known as AMDR (Air and Missile Defence Radar) which requires twice the electrical power of that of the flight IIAs. See Wikipedia (2017r) and Department of the Navy (2016a).