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Reducing Complexity in the RCAF With Constructive Simulation

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By Lieutenant-Colonel Matthew Parsons

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ABSTRACT

The accelerating use of emerging technologies in new Royal Canadian Air Force (RCAF) airpower capabilities is increasing effectiveness and availability but it introduces complexity that may increase cost, delay capability development, and elevate risk. These outcomes arise from challenges in defining requirements for products still in development, increasing the burden on test and evaluation, delaying tactics development, and lengthening training times. In the past, such concerns were addressed by accepting risk, accepting loss, increasing spending, and adopting new management practices but those mitigations are now either ineffective or undesirable.

Surprisingly, emerging technologies may also be a solution to these problems. Studies of available simulation resources, emerging simulation technologies, and personal and institutional acceptance of simulation indicate viability in building a constructive simulation capability that will support the development of new airpower capabilities. A constructive simulation can assess proposed requirements, initiate test and evaluation work, assess and optimize procedures in development, and can shorten training programs.

The challenge in developing the constructive simulation capability is it cannot be purchased off-the-shelf but must be developed in an interaction between elements of the simulation. This presents challenges with the Government of Canada (GoC) procurement regulations as they are designed to procure a product that meets the requirements rather than one that grows to meet the requirements.

The use of a hybrid Spiral Growth Project Model is recommended as a method to procure a constructive simulation capability for the RCAF.

CHAPTER 1. INTRODUCTION

Airpower is complex. It is complex to develop airpower capabilities, train in airpower capabilities, and employ airpower capabilities. Powered flight is a capability that has existed slightly over 100 years and has advanced from fabric and wood airplanes to a diverse array of digitally connected, automatic, and extremely capable aircraft. Emerging technologies have strong potential to enhance effectiveness, availability, and safety but they introduce complexity that may increase cost, delay capability development, and elevate risk. Interestingly, the underlying cause of this rise in complexity may also be a solution.

Within the RCAF, a new capability would arise from the identification of a need that existing capabilities cannot fulfill.[1] This need should not define a capability, rather it should identify requirements with which a capability must comply.[2] If the need were related to the capability gap that will arise as the RCAF's CF188 fighter aircraft fleet approaches retirement,[3] then the definition of the need itself will be complex and becomes even further complex as requirements and then potential solutions are considered.

The processes used by the RCAF and the Department of National Defense (DND) to develop and employ a capability are similar whether the new capability is as straightforward as a handheld radio or as complex as a new aircraft type used in a new role.[4] Introducing these capabilities into the RCAF involves processes where complexity

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[1] Canada. Department of National Defence, Project Approval Directive (PAD) (Ottawa, Canada, 2019), 52.
[2] Ibid., 55.
[3] Canada. Department of National Defence, 'Future Fighter Capability Project - Canada.Ca', Government of Canada, 28 September 2020, https://www.canada.ca/en/department-national-defence/services/procurement/fighter-jets/future-fighter-capability-project.html.
[4] Canada. Department of National Defence, Project Approval Directive (PAD).

has increased due to the emergence of new technologies, for example: defining the requirements,[5] testing of new equipment,[6] developing new operating procedures,[7] training personnel on the new equipment and procedures,[8] and managing the capability in a modern battlespace.[9] Using these example processes, the increased complexity and the detrimental impact to the employment of airpower due to the inclusion of emerging technologies is seen in the following paragraphs.

First, the development of technology is outpacing the GoC's ability to procure that technology, forcing the derivation of requirements for the new capability based on technologies that may not yet be used operationally,[10] and may not even be under development. This limits operational requirements personnel from proposing precise, forward-thinking requirements to define a new capability. Without precise requirements, there is risk in procuring suitably capable equipment and potential cost increase for updating requirements during the program.[11]

An increase in complexity is seen in the development and testing of new equipment to support the capability. For example, consider the flight test processes of newly developed aircraft. Simple 'stick and rudder' aircraft would be tested by establishing a small, safe operating envelope based on dozens of test conditions, and then probing beyond the limits of that envelope until it is expanded to be operationally

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[5] Ibid., 76.

[6] Ibid., 154.

[7] Canada. Department of National Defence, 'Air Force Orders', Royal Canadian Air Force, 30 April 2018, secs 8011–0, https://rcaf.mil.ca/en/c-air-force-staff/airforce-orders.page.

[8] Ibid., secs 5007–2.

[9] Canada. Department of National Defence, Royal Canadian Air Force Doctrine, 2nd ed (Ottawa: RCAF, 2015), 40.

[10] Canada and Office of the Auditor General, 'Acquisition of Military Helicopters.', Report of the Auditor General of Canada (Online) 2010 (2010): 6–14.

[11] Ibid., 6–16.

useful.[12] Modern aircraft can be considered more as 'bits and bytes' machines where every combination of every input to the aircraft should have one acceptable output (e.g., an aircraft operating at a particular speed and altitude that is given a control input of a particular size, should always respond in the same way). In this modern aircraft, a condition may be defined not just by speed and altitude but by dozens of sensors, each with a range of different output values. Establishing a small, safe operating envelope may require testing billions of test conditions.[13] Since it is not feasible to test the entire envelope, risk is accepted by testing only a subset of that envelope. [14]

Once the equipment is provided to the operational community with a safe operating envelope, the procedures and tactics to use that capability will need to be developed and proven effective.[15] The increased complexity of new technologies often results in more procedures to be tested and more detail in each procedure than older technologies would have required.[16] Furthermore, because of the rapid emergence of new technologies, this process may be the first opportunity to operate such equipment. With older technologies, much of the procedures and tactics could be assessed on similar platforms, before delivery of the new equipment.[17] The effect is that this essential process is delayed until the equipment is delivered with a safe operating envelope, and from that point takes more time than a similar effort would have taken in the past. If

[12] Alastair Cooke and Eric Fitzpatrick, Helicopter Test and Evaluation (John Wiley & Sons, 2009).
[13] Bill Read, 'Revolutionising Flight Test and Evaluation', Royal Aeronautical Society, 15 December 2020, https://www.aerosociety.com/news/revolutionising-flight-test-and-evaluation/.
[14] Cooke and Fitzpatrick, Helicopter Test and Evaluation.
[15] Canada. Department of National Defence, 'Air Force Orders', 8011–0.
[16] Read, 'Revolutionising Flight Test and Evaluation'.
[17] Cooke and Fitzpatrick, Helicopter Test and Evaluation.

extending the timeline to the new capability is unacceptable, then additional risk would be accepted that the procedures are unproven and thus potentially unsafe or ineffective.[18]

As the procedures and tactics are being developed, personnel must train on the new equipment and eventually learn the new procedures and tactics.[19] This creates a high demand for the equipment as multiple efforts require access to the same resources. Although this supply and demand challenge is not new to procurement projects, the rising cost and capability of modern equipment is causing a reduced number of assets being procured and an increase in the time required to learn the new capability, with the net effect of rising demand and a diminishing supply of the resources.[20] Additionally, modern technology often requires more assets to be used in a single training scenario to exercise the interoperability features.[21] This creates complexity in coordinating resources, further increases demand on the resources, and may risk insufficient training being provided to operators.

The last example of increased complexity in a new capability comes when using that capability as it was intended. The rise in technology is not occurring in isolation; adversaries are also benefitting from it. The tactics and procedures that were developed for the new capability may not have considered new adversarial capabilities. For example, when a new armed drone capability is first used in a battle, there may be a

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[18] Canada. Department of National Defence, 'Technical Airworthiness Authority Overview - Canada.Ca', Government of Canada, 15 March 2018, https://www.canada.ca/en/department-national-defence/services/military-airworthiness/technical-airworthiness-authority-overview.html.

[19] Canada. Department of National Defence, 'Defence Purchases and Upgrades Process', Government of Canada, 19 January 2017, https://www.canada.ca/en/department-national-defence/services/procurement/defence-purchases-and-upgrades-process.html.

[20] Canada and Office of the Auditor General, 'Acquisition of Military Helicopters.', 6–20.

[21] Eric Larson, Interoperability of Coalition Air Forces: Lessons Learned from U.S. Operations with NATO Allies (RAND Corporation, 2004), doi:10.7249/RB117.

previously unconsidered counter-drone defence.[22] The slower development process was experienced by adversaries in the past, so a new threat in battle was less likely, and if seen was probably not vastly different from other technologies.[23] Responding to such a threat may require completing any or all the above capability development processes while still in theatre.[24] The time, risk, and resource challenges still apply with the additional concern of being vulnerable until an updated capability is developed and proven. Completing developmental work while deployed to a hostile arena is itself a safety risk and it may drain personnel and resources that should be committed to the operation.

The increased complexity in each of the above processes is not a result of a sudden change in technology or any other area, rather it is a change that has been increasing complexity at an accelerating rate since airpower was first employed.[25] In the past, this was addressed by accepting risk, accepting loss, increasing spending, and adopting management practices from business, industry, and other militaries. None of those mitigations are proving sufficient to address the complexities the RCAF is experiencing today.

The underlying cause of these rises in complexity may also be a solution. Recent technological developments allow the above processes to be conducted or at least

[22] Dillon R. Patterson, 'Defeating the Threat of Small Unmanned Aerial Systems', Air & Space Power Journal 31, no. 1 (2017): 15.

[23] Warren Chin, 'Technology, War and the State: Past, Present and Future', International Affairs 95, no. 4 (1 July 2019): 765–83, doi:10.1093/ia/iiz106.

[24] Canada. Department of National Defence, 'Air Force Orders', secs 8011–0.

[25] Karl Mueller, 'Air Power', in The International Studies Encyclopedia (Oxford: Wiley-Blackwell, 2010).

supported in a simulation of the equipment, environment, and personnel.[26] Such *constructive simulations* do not require personnel to operate equipment for each test, do not require the actual equipment to be available, and may be able to complete all test conditions, rather than an achievable subset. The same constructive simulation that conducts tests may also replace an asset required for interoperability training or be used to rapidly evaluate new tactics in support of active hostilities.[27]

For most of the history of aviation, different forms of simulation have been used to help reduce the complexity of aviation and thus reduce the complexity of employing airpower.[28] Primarily, simulation has been used to create training devices that allow human interaction with a replica of the aviation environment. This allows extensive practice at a lower cost and allows aircrew to attempt dangerous manoeuvres without the risks of loss of life or damage to the aircraft.[29] Recent technological developments have improved the quality and speed of the simulations,[30] creating the opportunity to use constructive simulations to reduce complexity in the development, training, and employment of airpower capabilities.

The challenge with using a constructive simulation as a solution to the complex capability development problems is that the RCAF currently has the capability only to

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[26] Peter H Zipfel, 'CADAC: Multi-Use Architecture for Constructive Aerospace Simulations', The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology 9, no. 2 (April 2012): 129–45, doi:10.1177/1548512910395641.

[27] CAE Inc., 'Live-Virtual-Constructive (LVC) Training | CAE', 15 March 2021, https://www.cae.com/defence-security/training-systems-integration/live-virtual-constructive-lvc-training-1/.

[28] New World Encyclopedia, 'Flight Simulator', New World Encyclopedia, 13 April 2017, https://www.newworldencyclopedia.org/entry/Flight_simulator.

[29] Michael Masson, 'Use and Benefits of Simulators | EASA Community', European Union Aviation Safety Agency, 4 March 2021, https://www.easa.europa.eu/community/topics/use-and-benefits-simulators.

[30] CAE Inc., 'Full-Flight Simulators | CAE', CAE, 15 March 2021, https://www.cae.com/civil-aviation/aviation-simulation-equipment/training-equipment/full-flight-simulators/.

conduct a primitive constructive simulation or perhaps an elaborate constructive simulation of only a portion of a capability. To employ constructive simulations to aid in capability development, the RCAF must first develop what could become one of its most technologically advanced capabilities and must do this without experienced personnel, existing equipment, or proven procedures. Fortunately, there are development processes in other fields that will support building a constructive simulation capability through a long-term plan. It is anticipated that this must be a capability that starts small and grows into a *robust constructive simulation capability*, defined herein as “a team of RCAF and specialist personnel working in a top-secret facility with dedicated high-performance computer systems and a library of RCAF aircraft models, RCAF weapon models, and human pilot models.”

To confirm whether this proposed solution will support the RCAF’s future use of airpower this paper will address the question, “Should the RCAF develop a constructive simulation capability to address problems with developing airpower capabilities?”

THESIS

Many of the growing problems in the RCAF’s capability development originate from the increased complexity of developing, training, and employing new airpower capabilities. Earlier practices of accepting risk, accepting loss, increasing spending, and adopting new management practices are now either insufficient, ineffective, or undesirable. A constructive simulation capability, which replaces the human operator with a logical simulation of a human, will allow an analysis of the capabilities and designs before full development and without risk to equipment or personnel. Building a constructive simulation capability is in itself a complex challenge that must be addressed with innovative procurement and development methods. With a constructive simulation capability, the RCAF can use it to address the complexity of airpower and allow faster, safer, and more complete implementations of developing capabilities.

METHODOLOGY

The research question, "Should the RCAF develop a constructive simulation capability to address problems with developing airpower capabilities?" generated five objectives: confirm there is a problem with RCAF capability development, determine whether a constructive simulation is a viable means to address the problem, identify the existing support to the capability, determine additional elements required, and identify a means of procuring the capability. Research into government procurement progress was to identify problems with RCAF capability development. Research into existing and developing constructive simulation capabilities was to indicate the viability of using constructive simulation to address the problems. A historical review of simulation was to confirm support and existing resources. An analysis of the proposed capability was to identify procurement requirements. Finally, an analysis of procurement models was to identify a method of procuring the capability.

Much of the desired information was either classified or proprietary, and thus unusable in this paper, but sufficient material to form a conclusion was found by diversifying the sources. Government priorities and progress came from a 2017 policy document, two annual policy updates, RCAF major project updates, and a 2019 independent review from a think tank. The 2020 policy update had not yet been published. Effects of the global Covid-19 pandemic would first be indicated in that update, so did not affect this analysis. The RCAF and simulation historical review covers

1938 to the present day. It was sourced from official RCAF history websites, aviation museum publications, and RCAF and NASA history books. The research into constructive simulation capabilities included NASA history sources from the 1960s, peer-reviewed academic sources from 1974 to the present, academic books on simulation, and current magazine and industry websites. The analysis of the capability was a synthesis of the above research, based in part on the author's experience as a test pilot and an aerospace engineering researcher. The evaluation of the procurement models was a synthesis of GoC Acts, Treasury Board policies, DND policies, DND guidance for project management, and additional project models from software engineering and foreign military sources. The recommendation of a procurement strategy was a synthesis of the above material, guided in part by the author's experience as an RCAF Project Director for major simulator acquisition projects.

OUTLINE

This paper will define constructive simulations and will describe how they can be used to reduce complexity in airpower by supporting the development, training, and employment of airpower capabilities. It will identify different components of a constructive simulation capability and will relate them to the extant simulation capabilities of the RCAF. By considering the multi-dimensional effort that will be required to develop this capability, this paper will demonstrate a necessary and feasible approach towards the development of a constructive simulation capability through incremental development of a basic capability, an effective capability, and ultimately a robust constructive simulation capability.

Chapter 2 begins by providing some essential technical background and definitions. Although the topic of this paper is about the development of the capability throughout the RCAF and not solely about the technology and engineering, a base understanding of the constituent technologies is needed to identify some of the challenges in developing this capability. It continues with a review of literature that contributed to and supported this analysis. It was necessary to draw from many fields as this paper is focusing on a capability for which little is written as the capability does not yet exist within the RCAF and is in its infancy in aerospace beyond the RCAF.

Chapter 3 examines progress on the GoC and DND goals for the RCAF to confirm that there is a problem with developing and employing new capabilities. The potential for a constructive simulation capability to address GoC initiatives by streamlining procurement and developing innovation is detailed. The ability for constructive simulation to reduce complexity is demonstrated using examples from aerospace and other fields. The need to develop a constructive simulation capability follows as a method to achieve those gains.

Chapter 4 discusses milestones in simulation and aerospace to address what is best described as *buy-in*. Buy-in is a common obstacle to employing simulation that is an essential component in building a constructive simulation capability for the RCAF. Buy-in is the individual, community, and departmental acceptance of simulation, often in lieu of established practices. The history of aerospace and simulation milestones will show a continuous increase in simulation capabilities as well as an increasing buy-in to the expanding uses of simulation that culminates in the 2014 RCAF Simulation Strategy[31] and the increased use of simulation in pilot training.

Chapter 5 focuses on current RCAF use of simulation, existing simulation capabilities, and some external capabilities that support the RCAF. Within these capabilities, there are components in use that will support constructive simulation. It examines the availability of simulation-trained personnel and the availability of such training. This overview of RCAF simulation will add to the argument that there is sufficient buy-in within the RCAF to initiate the development of a constructive simulation capability.

Chapter 6 identifies the elements of a constructive simulation capability: computer hardware, software models, personnel, and problems to solve. For each of these elements, this paper will identify attributes unique to the RCAF, will examine existing capabilities within DND, GoC, and industry, and will identify co-dependencies between requirements that create challenges in developing a robust constructive simulation capability.

Chapter 7 considers methods of developing constructive simulation capabilities. Known challenges with the GoC procurement are presented with their likely impact on developing a constructive simulation capability. A method of growing a capability called spiral development is presented and compared with traditional capability development models. The chapter concludes with a recommendation of a hybrid project model based on GoC models and the spiral development concept.

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[31] Canada. Department of National Defence, RCAF Simulation Strategy 2025 (Royal Canadian Air Force, 2014).

Finally, Chapter 8 summarizes the findings and by showing there is need, value, and buy-in within the RCAF for a constructive simulation capability will conclude that a series of projects be initiated to develop increasingly complex constructive simulation capabilities.

CHAPTER 2. TERMINOLOGY AND LITERATURE REVIEW

This proposed RCAF constructive simulation capability is a technologically demanding topic that is filled with engineering concepts and challenges. This paper is less about technology and more about the procurement and development of that capability and whether it would be a suitable solution for the problems with airpower complexity. Still, a foundational understanding of the constituent technologies is needed to identify some of the challenges in the development of a constructive simulation capability. Using standard simulation industry sources, key terminology is introduced with some discussion to relate concepts to this analysis.

TERMINOLOGY

Wherever possible, the definitions are sourced from the United States Department of Defense publications *Modeling and Simulation Master Plan*[32] and *Modeling and Simulation Glossary*[33] as these have become guidance documents used by much of the simulation industry when developing new simulation technologies. As is true with many emerging capabilities, international standards have either not been written or have not fully been adopted and much of the literature will use different definitions for similar capabilities.

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[32] Under Secretary of Defense for Acquisition and Technology, Modeling and Simulation (M&S) Master Plan (Department of Defense, 1995).

[33] Under Secretary of Defense for Acquisition and Technology, DoD Modeling and Simulation (M&S) Glossary (Department of Defense, 1998).

Simulation Terminology

A *simulation* is “a method for implementing a model over time.”[34] A *model* is “a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process.”[35] A simulator is the “device, computer program, or system that performs simulation.”[36] To illustrate these definitions, consider an aircraft simulator that runs a simulation to train aircrew. While a single model could be built to simulate every aspect of the aircraft, there are many reasons to use multiple models.

The flight dynamics model is an essential model that allows the representation of an actual aircraft’s behaviour.[37] It provides the simulation of the effect of control inputs on the flight, the behaviour of the aircraft following a disturbance in flight, and the performance characteristics of the aircraft such as the maximum weight, the stalling speed, or the landing behaviours. An engine model would communicate the thrust that the engine would produce to the flight dynamics model but would also determine operating parameters that the aircrew would need to monitor such as engine temperatures and fuel flow.[38] A terrain model would contain features such as geography or navigation facilities[39] that may be used to generate visuals or to fly the simulator between locations.

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[34] Ibid., 157.
[35] Ibid., 138.
[36] Ibid., 158.
[37] Mark E. Dreier, Introduction to Helicopter and Tiltrotor Simulation, AIAA Education Series (Reston, VA: American Institute of Aeronautics and Astronautics, 2007), 41.
[38] Ibid., 371.
[39] Under Secretary of Defense for Acquisition and Technology, DoD Modeling and Simulation (M&S) Glossary, 96.

Fidelity

Fidelity is "the accuracy of the representation when compared to the real world."[40] It is typically used with the implication that it is quantifiable but, at best, it is only relatively quantifiable in that one simulation may be considered to have higher fidelity than another. More likely, two similar simulations will vary in their fidelity in different areas. Achieving the best fidelity in any one area is rarely a goal, rather the fidelity is selected to be sufficient for the intended task of the simulator.

Control

If an object, such as an airplane, requires human control for it to operate then a simulation of that object will also require control. The two methods of implementing control in a simulation are to use an actual human controlling the simulation or to create a model of human behaviour that simulates human control.[41] A simulation where the *simulant*, or the system being simulated, is represented by a model and the control is completed by a human is called a *virtual simulation*.[42] When the control is completed by a model of human behaviour, the simulation is called a *constructive simulation*.[43] A third simulation domain, *live simulation*,[44] is often discussed where actual humans are operating actual systems and the simulation is the activity. Live simulation includes all

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[40] Ibid., 119.
[41] Dreier, Introduction to Helicopter and Tiltrotor Simulation, 411.
[42] Under Secretary of Defense for Acquisition and Technology, DoD Modeling and Simulation (M&S) Glossary, 132.
[43] Ibid.
[44] Ibid.

the RCAF's Force Generation flying, which consumes most of its costly annual flying budget.[45]

The difference between virtual and constructive simulation is clear only in definition, but not in practice. For example, the use of an autopilot by a human during a virtual simulation could fit into both categories. Within this paper, constructive simulations do not require real-time human input. While a human will *act* by operating the computer and generate commands that control the simulation, the models will execute without the human *reacting* within the simulation.

Computer Generated Forces (CGF) refer to "computer representations of [objects] in a simulation that attempt to model human behaviour,"[46] allowing the objects to respond without a person controlling the simulation. For example, an enemy fighter in an air battle simulation may be represented with a CGF. Arguably, a CGF is a constructive simulation within a larger live, virtual, or constructive simulation.

Time

Time is measured in a simulation in two different ways. Although a simulation is implementing a real model over time, the simulation may run at a different rate than the simulant would run. *Simulated time* is the elapsed time within the model.[47] *Actual time* is the elapsed time in real life. If one second of simulated time equals one second of

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[45] Canada. Department of National Defence, 'Evaluation of Air Force Readiness - Canada.Ca', October 2017, https://www.canada.ca/en/department-national-defence/corporate/reports-publications/audit-evaluation/evaluation-air-force-readiness.html.

[46] Under Secretary of Defense for Acquisition and Technology, DoD Modeling and Simulation (M&S) Glossary, 98.

[47] Ibid., 157.

actual time, the simulation is said to be running in *real-time*.[48] This generates three relative time considerations that are illustrated by these examples:

Real-time occurs when simulated time passes at the same rate as actual time. Training flight simulators operate in real-time because they intend to train pilots to operate real aircraft and need the response times to be represented.

Slow Time occurs when simulated time passes slower than actual time.[49] In the engineering branch of computational fluid dynamics, a constructive simulation will use physics models to determine the flow of air around an object (perhaps a wing). Without extremely powerful computers, the vast number of calculations normally means that one second of simulated time is calculated over hundreds or thousands of seconds of actual time (i.e. the computer will run for hours and will calculate one second of a simulation).[50]

Fast Time occurs when simulated time passes faster than actual time.[51] A Monte Carlo simulation is an analysis method used when exact solutions can not be solved. For example, with multiple routes between work and home, and knowing speed limits and the traffic patterns, it should be possible to find the quickest route home. Solving this as a large set of equations may take a long time with a powerful computer or may even be impossible.[52] In a Monte Carlo simulation, every route home would be drive, starting at different departure times, to find the optimum departure time and route from the data set. A human may take weeks to drive only a small subset of this data but a constructive

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[48] Ibid., 152.

[49] Ibid., 160.

[50] John D. Anderson, Computational Fluid Dynamics: The Basics with Applications, 8th ed., McGraw-Hill Series in Mechanical Engineering (New York: McGraw-Hill, 2001).

[51] Under Secretary of Defense for Acquisition and Technology, DoD Modeling and Simulation (M&S) Glossary, 114.

[52] Emanuele Vitali et al., 'An Efficient Monte Carlo-Based Probabilistic Time-Dependent Routing Calculation Targeting a Server-Side Car Navigation System', ArXiv:1901.06210 [Cs], 18 January 2019, http://arxiv.org/abs/1901.06210.

simulation that models the driver, car, and traffic patterns could 'drive' each route in fractions of a second and provide a result almost immediately (actual time) even though it is 'driving' many routes over weeks (simulated time).

Simulation Concepts

The development and use of a model would be of little value if the accuracy of the model is unknown. As simulations get more complex, assuring a model is an accurate representation also becomes more complex. This is determined through *Verification and Validation*. Each is a formal process that together ensures the model is suited for its intended use and that the model "accurately represents the…specification."[53]

With a live or virtual simulation, one intent is for the human to be unaware that it is a simulation, and thus will react and learn appropriately. This is called the *suspension of disbelief* from Samuel Taylor Coleridge's description of poetic faith[54] but has morphed into a common but perhaps elusive goal in simulation.[55]

Negative learning is the consequence of a failure to provide the correct simulation. It is in common use in many learning and simulation fields but is not formally defined. It is recognized after the training occurs by a student who has developed the wrong skills or has misunderstood the knowledge from the simulation.

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[53] Under Secretary of Defense for Acquisition and Technology, DoD Modeling and Simulation (M&S) Glossary, 170.

[54] Samuel Taylor Coleridge, Biographia Literaria (Project Gutenberg, 1817), chap. XIV, https://www.gutenberg.org/files/6081/6081-h/6081-h.htm.

[55] Mikkel Marfelt, 'The Holy Grail of Virtual Reality (VR): A Complete Suspension of Disbelief', LinkedIn, 1 September 2016, https://www.linkedin.com/pulse/holy-grail-virtual-reality-vr-complete-suspension-mikkel-marfelt.

Organizational Functions

Elements of an airpower capability can be categorized using the functions of the 5F Organizational Model proposed in the *Report on Transformation 2011*: Force Development (FD), Force Generation (FG), Force Employment (FE), Force Support (FS), and Force Management.[56]

FD is "a system of integrated and interdependent processes used to identify, conceptualize, and implement necessary changes to existing capabilities or to develop new capabilities."[57] FG is "The process of organizing, training and equipping forces for force employment."[58] FE is "1. At the strategic level, the application of military means in support of strategic objectives. 2. At the operational level, the command, control and sustainment of allocated forces."[59]

LITERATURE REVIEW

A robust constructive simulation capability does not yet exist within the RCAF and is in its infancy in aerospace efforts beyond the RCAF. Many of the concepts discussed throughout this paper are emerging technologies in the aerospace, simulation, or computer science fields so there is not an extensive catalogue of sources. The information from GoC and DND is limited to the unclassified domain. Many of the latest developments come from industry which further limits availability to protect their intellectual property. Because these technologies have a foundation in prior concepts,

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[56] Andrew Leslie, 'Report on Transformation 2011', Government of Canada, 23 August 2016, https://www.canada.ca/en/department-national-defence/corporate/reports-publications/report-on-transformation-2011.html.

[57] Canada. Department of National Defence, 'Defence Terminology Bank (DTB)', Canadian Armed Forces, accessed 5 February 2021, http://terminology.mil.ca/term-eng.asp, Record 32172.

[58] Ibid., Record 32171.

[59] Ibid., Record 32173.

older academic articles supported by news items and industry sources together can support many of the positions.

The identification of a problem with aerospace procurement, training and employment arises primarily by comparing the GoC initiatives listed in *Strong. Secure. Engaged. (SSE)*[60] with the 2018 *Department Investment Plan*,[61] its 2019 *Annual Update*,[62] and with the 2019 review of SSE from the Canadian Global Affairs Institute.[63] The progress indicated in those reports was compared with two RCAF projects, the Cyclone helicopter procurement[64] and the Fixed-Wing Search and Rescue Airplane Replacement (FWSAR) program[65] Together, these reports showed progress on lower-cost initiatives but stagnation on the higher cost RCAF projects.

The aerospace research conducted by the United States in the 1960s through the National Aeronautics and Space Administration identified areas of technology development that support the concept of using constructive simulation early in an aircraft's development. *Wingless Flight: The Lifting Body Story*[66] showed a successful development of a flight model in 1965 that predicted sequences that would be

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[60] Canada. Department of National Defence, Strong, Secure, Engaged - Canada's Defence Policy., 2017, http://epe.lac-bac.gc.ca/100/201/301/weekly_acquisitions_list-ef/2017/17-23/publications.gc.ca/collections/collection_2017/mdn-dnd/D2-386-2017-eng.pdf.

[61] Canada. Department of National Defence, 'Defence Investment Plan 2018' (Ottawa, Canada, 12 October 2018).

[62] Canada. Department of National Defence, 'Defence Investment Plan 2018 - Annual Update 2019' (Ottawa, Canada, 12 July 2019).

[63] David Perry, Strong, Secure, Engaged: A Two-Year Review, 2019, https://www.deslibris.ca/ID/10100551.

[64] 'CH-148 Cyclone. Canada's Maritime Helicopter', Lockheed Martin, 2021, https://www.lockheedmartin.com/en-us/products/sikorsky-ch148-cyclone-helicopter.html.

[65] Canada. Department of National Defence, 'Fixed-Wing Search and Rescue Procurement Project', Government of Canada, 17 September 2020, https://www.canada.ca/en/department-national-defence/services/procurement/fixed-wing-search-and-rescue-procurement-project.html.

[66] R. Dale Reed and Darlene Lister, Wingless Flight: The Lifting Body Story, NASA SP 4220 (Washington, DC: National Aeronautics and Space Administration ; For sale by the U.S. G.P.O., Superintendent of Documents, 1997).

challenging for human pilots and allowed the actual human pilots to rehearse those sequences through simulation. *Computers in Spaceflight: the NASA Experience*[67] discussed the advances in the use of digital computing and the development of flight models in support of the Space Race. The book *Journey into Space Research*[68] discussed the use of a training simulator in 1969 and how it was able to help a scientist solve challenging air combat mathematical problems, showing potential in procedure and tactics development through simulation.

The developments towards the current use of simulation in the RCAF are demonstrated from numerous historical and current data sources. These include a GoC RCAF History website,[69] a book covering personal RCAF experiences in the 1970s,[70] and a website with the history of CAE,[71] a Canadian simulator company with close ties to the RCAF. The current inventory of simulators in the RCAF comes from a DND website[72] and a Flight Global magazine report.[73] RCAF training policies[74] provide insight into the use and acceptance of the training simulators while the 2014 RCAF Commander's guidance on the future of simulation[75] provides the broader vision of how simulation should develop. It includes constructive simulation.

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[67] James E. Tomayko, Computers in Spaceflight: The NASA Experience (Pittsburgh, Pennsylvania: National Aeronautics and Space Administration, 1987), https://history.nasa.gov/computers/contents.html.

[68] W Hewitt Phillips, 'Journey Into Space Research', Monographs in Aerospace History, no. 40 (July 2005): 45.

[69] Canada. Department of National Defence, 'Royal Canadian Air Force History', Government of Canada, n.d., https://www.canada.ca/en/air-force/services/history.html.

[70] John Charles Corrigan, The Red Knight, 2017, http://epe.lac-bac.gc.ca/101/200/300/friesenpress/john_charles_corrigan/red/index.html.

[71] CAE Inc., 'About CAE - History', CAE, 2021, https://www.cae.com/about-cae/history/.

[72] Canada. Department of National Defence, 'Simulators and Trainers', National Defence, 23 January 2021, http://materiel.mil.ca/en/air-equipment/simulators.page.

[73] FlightGlobal and CAE, 'Military Simulator Census 2020' (FlightGlobal, 4 December 2020), https://www.flightglobal.com/reports/military-simulators-census-2020/141458.article.

[74] Canada. Department of National Defence, Flight Operations Manual (Winnipeg, Canada: Commander 1 Canadian Air Division, 2021).

[75] Canada. Department of National Defence, RCAF Simulation Strategy 2025.

The existing use of constructive simulation in the RCAF included the 2015 handling qualities evaluation of the Chinook helicopter,[76] the development of ship airwake data using models and tests,[77] and the implementation of ship airwake simulations in support of Cyclone helicopter ship trials.[78] The Chinook project also used a human pilot in a virtual simulation to verify project design, confirm deliverables, and develop procedures.[79] Each of these projects was conducted by external agencies in support of the RCAF, so do not represent an RCAF capability but do demonstrate the value of constructive simulation in supporting RCAF projects and tactic development.

A core concept in a robust RCAF constructive simulation capability is the need to have an accurate model of a human pilot that can control the simulation and make decisions. The 1974 work, *Mathematical Models of Human Pilot Behavior*[80] is the basis for many human pilot models, but only mimics a pilot in a linear control system by including a delay to represent neuro-muscular lag. This is a good model when pilots are "hands-on attentive"[81] but not when pilots are monitoring the flight and responding only as needed. Advanced human pilot models have been developed for specific applications

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[76] Christopher Colosi et al., 'ADS-33 Evaluation of the International CH-47 Chinook', in Journal of AHS (American Helicopter Society International Forum 71, Virginia Beach, VA: Vertical Flight Society, 2015).

[77] Weixing Yuan, Richard Lee, and Alanna Wall, 'Simulation of Unsteady Ship Airwakes Using Openfoam' (International Council of the Aeronautical Sciences, Daejon, Korea, 2016), 10.

[78] Eric Thornhill, 'Guidelines for Performing Ship Airwake Simulations on a Generic Destroyer' (Halifax, Canada: DRDC - Atlantic Research Centre, April 2019).

[79] Mark Daghir et al., 'CH147F Crew Stations Interface Document' (Philadelphia, PA: The Boeing Company, n.d.).

[80] D. T. McRuer and E. S. Krendel, 'Mathematical Models of Human Pilot Behavior' (NATO Science and Technology Organization, 1 January 1974), http://www.cso.nato.int/Pubs/rdp.asp?RDP=AGARD-AG-188.

[81] The United Kingdom. Ministry of Defence, Certification Specification for Airworthiness, DEF STAN 00–970 (Glasgow: Ministry of Defence, 2021).

including air combat,[82] flight test,[83] and shipborne helicopter manoeuvres[84] but these are not intended to be used in other simulations. The logical decision-making processes of a pilot were studied as artificial intelligence in 2000[85] and have been represented with fuzzy logic[86] in 2003 and with neuroadaptive cognitive modelling in 2020.[87] The developments of human pilot modelling are advancing with current technology trends, suggesting future advancement in support of a robust constructive simulation capability will continue.

The procurement of a constructive simulation capability must follow the GoC and DND *Defence Purchases and Upgrades Process*,[88] which is subject to the *Defence Production Act*,[89] and the *Financial Administration Act*.[90] Guidance for the management of projects from the Treasury Board[91] and in the DND *Project Approval Directive*[92] indicates different project models including cyclical and multi-phase projects. To allow

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[82] G. H. Burgin and L. B. Sidor, 'Rule-Based Air Combat Simulation', NASA Contractor Report (Ames Research Center, 1988).

[83] Mohammad M Lone and Alastair K Cooke, 'Pilot-Model-in-the-Loop Simulation Environment to Study Large Aircraft Dynamics', Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 227, no. 3 (March 2013): 555–68, doi:10.1177/0954410011434342.

[84] Matthew R. Parsons and Robert G. Langlois, 'Stability Analysis of a Two-Dimensional Tethered Helicopter', in Proceedings of the 3rd International Conference on Control, Dynamic Systems, and Robotics, 2016, doi:10.11159/cdsr16.128.

[85] Rob Richards and US Department of Defense; Defense Technical Information Center, 'Artificial Intelligence Techniques for Pilot Approach Decision Aid Logic (PADAL) System: (437832006-001)' (American Psychological Association, 2000), doi:10.1037/e437832006-001.

[86] Masoud Mohammadian, Ruhul A. Sarker, and Xin Yao, Computational Intelligence in Control (Hershey: Idea Group Pub, 2003).

[87] Oliver W Klaproth, 'Tracing Pilots' Situation Assessment by Neuroadaptive Cognitive Modeling', Frontiers in Neuroscience 14 (2020): 13.

[88] Canada. Department of National Defence, 'Defence Purchases and Upgrades Process'.

[89] Canada. Minister of Justice, 'Defence Production Act', Pub. L. No. R.S.C, 1985, c. D-1 (2017), https://laws-lois.justice.gc.ca/eng/acts/D-1/.

[90] Canada. Department of Justice, Financial Administration Act, Revised Statutes of Canada, 1985, c. F-11, 2021, https://laws-lois.justice.gc.ca/eng/acts/f-11/page-1.html.

[91] Canada. Treasury Board, 'Directive on the Management of Projects and Programmes', Government of Canada, 11 April 2019, https://www.tbs-sct.gc.ca/pol/doc-eng.aspx?id=32594.

[92] Canada. Department of National Defence, Project Approval Directive (PAD).

this capability to grow, the notion of a spiral development[93] applied to government procurement[94] is considered. Considerations regarding outsourcing this capability are guided by concerns of Sir Charles Haddon-Cave[95] on outsourcing military airworthiness work and by outsourcing challenges in the Information Technology domain.[96]

The concept of using computer clusters to develop supercomputers in support of this capability is based on a 2001 journal article and a 2012 Time article that provide very rough cost and performance information. The viability of the cluster is supported through details on the GoC's[97] and Canadian industry supercomputing capabilities.[98]

CONCLUSION

The following chapters will demonstrate the need, the support, the technical challenges and the procurement challenges identified in the above research. Some simulation technologies are discussed throughout that, with the foundational understanding provided in this chapter by the terminology and concepts, will support linking the proposed solution with the airpower complexity problem and the procurement challenges.

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[93] B. W. Boehm, 'A Spiral Model of Software Development and Enhancement', Computer 21, no. 5 (May 1988): 61–72, doi:10.1109/2.59.

[94] Jacques S. Gansler, William Lucyshyn, and Adam Spiers, 'Using Spiral Development to Reduce Acquisition Cycle Times': (Fort Belvoir, VA: Defense Technical Information Center, 1 September 2008), doi:10.21236/ADA494266.

[95] Charles Haddon-Cave, 'Leadership & Culture, Principles & Professionalism, Simplicity & Safety - Lessons from the Nimrod Review', in Judiciary of England and Wales ('Piper 25' Oil & Gas UK Conference, Aberdeen, Scotland, 2013).

[96] Stephanie Overby, 'What Is Outsourcing? Definitions, Best Practices, Challenges and Advice', Chief Information Officer, 6 November 2017, https://www.cio.com/article/2439495/outsourcing-outsourcing-definition-and-solutions.html.

[97] Shared Services Canada, 'High Performance Computing', Government of Canada, 2 November 2017, https://www.canada.ca/en/shared-services/corporate/data-centre-consolidation/high-performance-computing.html.

[98] Erich Strohmaier et al., 'TOP500 List - November 2020', November 2020, https://top500.org/lists/top500/list/2020/11/.

CHAPTER 3. THE NEED

Constructive simulation is proposed as a means to reduce complexity in the development, training, and employment of a Canadian aerospace capability. Before a proposed solution can be implemented, the deficiency or future requirement must first be established. Multiple solutions are proposed and vetted against the deficiency or requirement before one solution is selected. Following the GoC and DND methods for capability development, a Business Case Analysis would be created to vet the options and allow selection of the better course of action. This creates a challenge in developing unproven technologies into new capabilities in that the GoC Project Approval process requires that the Business Case confirms that the "intended benefits are…relevant and attainable"[99] and demonstrates an "ongoing viability of the project."[100] Attainable benefits and viability are demonstrated easily with proven technologies but cannot be guaranteed with emerging technologies. Rather than claiming that a constructive simulation capability is the best course of action to reduce complexity, this chapter will first show that the department's policies are not being achieved, creating a deficiency, and then will show that constructive simulation directly supports some of the departmental goals. Lastly, this chapter will show the potential for constructive simulation to be a viable course of action in supporting the achievement of procurement goals.

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[99] Canada. Treasury Board, 'Directive on the Management of Projects and Programmes', chap. 4.
[100] Ibid.

GOC AND DND PRIORITIES

The GoC released a Defence Policy, *Strong. Secure. Engaged.* (SSE), in 2017 that provided a multi-year plan of change and procurement. It included 111 initiatives that include 13 major procure projects for the RCAF, including at least nine new aircraft platforms.[101] The RCAF's progress in advancing new capabilities is measured first by achieving procurement goals, and then by supporting the GoC direction of *Anticipate. Adapt. Act*.

Achieving Procurement Goals

A challenge with SSE is that it neither acknowledges the effort nor identifies the source of the personnel required to implement these programs. Some of this effort is mentioned in the *Defence Purchases and Upgrade Process*[102] in that the work defined at each of the five stages of a project (Identification, Options Analysis, Definition, Implementation, and Close-out) requires teams of personnel that represent a diversity of specialties. There is more effort outside those five stages in that the methods of employing the new capability must be developed, proven valid, and then taught to the personnel using or supporting the capability. The level of effort for each task increases with the complexity of the project.

Consider the examples of complexity from Chapter 1. The work of the operational requirements personnel proposing forward-thinking requirements to define a new capability corresponds to "the project team prepares a… business case analysis of the options"[103] in the definition phase. The development and testing of new equipment

[101] Canada. Department of National Defence, Strong, Secure, Engaged - Canada's Defence Policy., 39.
[102] Canada. Department of National Defence, 'Defence Purchases and Upgrades Process'.
[103] Ibid.

correspond to "complex equipment is usually tested and verified by DND and CAF"[104] in the implementation phase. The training of personnel on new equipment corresponds to "CAF members are trained on its use,"[105] also in the implementation phase. The development, evaluation, and training of tactics and procedures are essential to the implementation of the capability but are not procurement tasks so are not included in the *Defence purchases and upgrades process*.[106]

SSE does not provide deadlines for completing its initiatives, creating a challenge to determine whether policy requirements are being achieved. Success may be inferred from SSE progress reports by determining the completed versus the remaining effort in implementing the initiatives. The *Defence Investment Plan 2018*[107] indicates that two years after SSE was released, 68% of the SSE Capital Projects were in implementation or close-out phase. The 2019 update[108] indicated that 68% remained in implementation or close-out phase and claims that projects are advancing yet none have progressed into close-out.

Greater awareness is seen by comparing projected defence capital spending from SSE with the actual capital spending. Figure 3.1 shows approximately $2 billion annual shortfall, or slightly more than 60% of projected, between 2017 and 2019. To catch up and spend the money to complete the intended procurements, the annual shortfall must be added to the next year's projections. If the underspending continues then the shortfall rises rapidly, exceeding $25 billion by the end of 2023. This is shown in Figure 3.2.

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[104] Ibid.
[105] Ibid.
[106] Ibid.
[107] Canada. Department of National Defence, 'Defence Investment Plan 2018'.
[108] Canada. Department of National Defence, 'Defence Investment Plan 2018 - Annual Update 2019'.

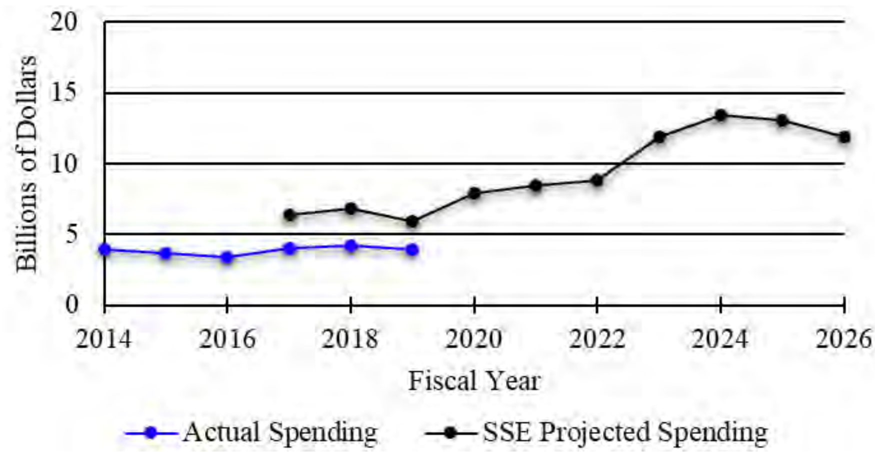

Figure 3.1 – Canadian Defence Capital Funding[109]

The actual defence capital funding from 2014 to the present and the projected funding required to support SSE from its 2017 release to 2026 are shown in Figure 3.1. The capital spending fell short an average of 36.5% annually from 2017 to 2019. The effect of that shortfall is under-represented in the data as it must be added to the projection to keep the projects on schedule.

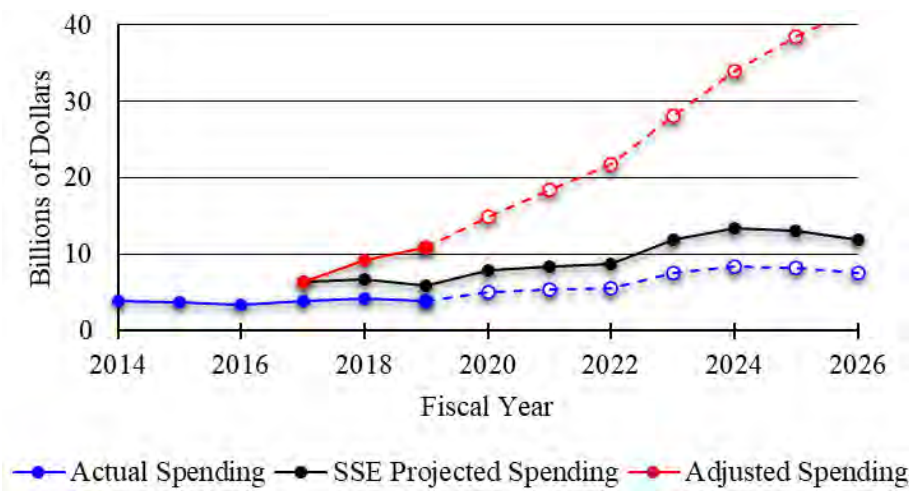

Figure 3.2 –Defence Capital Funding with Effect of Spending Shortfall[110]

The adjusted SSE spending is shown in red in Figure 3.2. The dashed lines indicate the effect of the assumed 36.5% shortfall in SSE spending continues, even with

[109] Perry, Strong, Secure, Engaged: A Two-Year Review.
[110] Ibid.

the adjusted spending values. Figure 3.2 is a more accurate picture of the effect of the shortfall on project schedules and thus completion of SSE initiatives.

The status of the nine RCAF aircraft procurement projects indicates that four years after SSE was released, none are in close-out and only the FWSAR project is in implementation. FWSAR had a contract awarded before SSE release yet has only just begun the development of tactics and the training of operational personnel.[111]

The announcement that 68% of SSE Capital Projects are in implementation or close-out suggests accomplishment of GoC priorities, yet the spending shortfalls and the delayed procurement of aircraft suggest otherwise. Although many smaller, less costly projects are advancing, the complex projects necessary for RCAF essential missions are not.

Anticipate. Adapt. Act.

SSE also provides direction on a new Canadian approach to defence titled, "Anticipate. Adapt. Act."[112] that includes direction for "leveraging innovation, knowledge, and new ways of doing business"[113] that include finding innovative solutions to Defence challenges and streamlining procurement. SSE identifies that "while 90 percent of projects are delivered within their planned scope and budget…a small segment of complex, high-value equipment projects have faced significant challenges."[114] The other failing identified by SSE is that "70 percent of all projects have not been delivered on time,"[115] when discussing projects delivered before SSE. Although SSE does not

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[111] Canada. Department of National Defence, 'Fixed-Wing Search and Rescue Procurement Project'.
[112] Canada. Department of National Defence, Strong, Secure, Engaged - Canada's Defence Policy., 63.
[113] Ibid.
[114] Ibid., 74.
[115] Ibid.

offer a solution to the delays or the significant challenges, it is clear that an innovative solution that can address both of those would align well with SSE's intent.

THE CONSTRUCTIVE SIMULATION SOLUTION

The slow progress of SSE initiatives is a problem for which constructive simulation is proposed as a solution. However, SSE was intended to be a comprehensive approach that "will provide the CAF with the force size and equipment required"[116] to fulfill the core missions. Any procurement that is not detailed in SSE may be considered extraneous to the needs of the CAF. Identifying direct alignment of the constructive simulation capability with SSE initiatives provides the policy cover[117] that is essential for a project to be supported. Following is a discussion of the initiatives aligned with constructive simulation and an outline of the means that a constructive simulation will reduce complexity.

Alignment with SSE

Three procurement initiatives are directly aligned with developing a constructive simulation capability: SSE Initiative #94, "reduce project development [time]…for low-risk and low-complexity projects,"[118] SSE Initiative #96, "use procurement to incentivize Canadian research and development in important and emerging technological areas,"[119] and SSE Initiative #98, "grow and professionalize the defence procurement workforce in order to strengthen the capacity to manage the acquisition and support of today's

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[116] Ibid., 11.
[117] Canada. Department of National Defence, Project Approval Directive (PAD), 272.
[118] Canada. Department of National Defence, Strong, Secure, Engaged - Canada's Defence Policy., 75.
[119] Ibid.

complex military capabilities."[120] The constructive simulation capability will build an R&D capability that relies on emerging technologies to strengthen acquisition processes and shorten development times.

SSE Initiative #105 is a plan to invest in innovation that includes "creating clusters of defence innovators (academics, industry, and other partners) to conduct leading-edge research and development in areas critical to future defence needs."[121] Assembling a team of innovators is only a part of an innovative solution, as they also need special tools to support their work. For example, the mathematicians at Bletchley Park would not have been able to decrypt German Enigma transmissions[122] without first building a Bombe,[123] their mechanical computer that executed Monte Carlo simulations of the code possibilities. Chapter 6 will identify a team of specialist personnel as an essential element of a constructive simulation capability. Developing a constructive simulation capability will support Initiative #105 and will exceed it by ensuring those researchers have the advanced tools they require.

Reducing Complexity

With constructive simulation aligned with SSE Initiatives, procurement of the capability can have policy support. Yet for the procurement to proceed, it must also be a viable solution for the identified deficiency.[124] To demonstrate the viability of the constructive simulation capability, it is important to consider the span of support it can

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[120] Ibid.
[121] Ibid., 78.
[122] The Editors of Encyclopedia Britannica, 'Bletchley Park', in Britannica (Encyclopædia Britannica, 30 December 2018), https://www.britannica.com/place/Bletchley-Park.
[123] 'Bombe', Wikipedia. The Free Encyclopedia, 30 March 2021, https://en.wikipedia.org/wiki/Bombe.
[124] Canada. Treasury Board, 'Directive on the Management of Projects and Programmes'.

provide. For an airpower capability, this span can be categorized under three functions of the *5F Organizational Model*: FD, FG, and FE.[125]

Force Development

As discussed in Chapter 1, the incorporation of advanced technologies has increased the FD effort by challenging the requirements definitions, extending the test and evaluation load, and increasing the amount and complexity of new tactics and procedures. In the past, much of the developmental work could be completed on similar types because the equipment did not change considerably. With the rapid emergence of technology, new RCAF equipment is often unique so testing on similar types is impossible.

To demonstrate the acceleration of the new technology, compare the images of five RCAF helicopter instrument panels in Figure 3.3, as they would have appeared on the year introduced to service. The cockpits were developed for similar flight environments (day and night, including flight in clouds). The images show very few cosmetic changes from 1954 until the introduction of the CH149 Cormorant in 2000 where computer screens are included with some analog gauges. In 2012 the RCAF began flying the CH147F Chinook that was filled with interactive computer screens that displayed all flight and mission information to the pilots. This technology acceleration is continuing with the CH148 Cyclone that has replaced mechanical pilot control with a fly-by-wire system where a pilot provides input to a computer, which then moves the control linkages.[126] For more than 45 years, the appearance of the cockpits remained very

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[125] Leslie, 'Report on Transformation 2011'.
[126] 'CH-148 Cyclone. Canada's Maritime Helicopter'.

similar, making the testing, procedure development, and training also very similar. In the last twenty years, each new helicopter fleet represents large steps forward in technology and the associated increases in the test, procedure development, and training burdens.

1954 – CH125 Workhorse[127]

1982 – CH113 Labrador[128]

1994 – CH146 Griffon[129]

2000 – CH149 Cormorant[130]

2012 – CH147F Chinook[131]

Figure 3.3 – RCAF helicopter cockpits over time.

The effect of this accelerating introduction of technology on FD efforts can be seen by comparing the test and evaluation programs that accepted two of these helicopters. There was no time spent dedicated to testing the CH146 Griffon instrument panel as the instruments are ground-calibrated by technicians and then verified during other flight manoeuvres. Over 500 person-hours were spent by the RCAF dedicated to testing the 2756 pages of CH147F mission systems specifications.[132]

Surprisingly, the CH147F program was implemented very rapidly and on schedule, achieving first aircraft delivery within four years of contract signing, and Initial Operating Capability less than two years later. This rapid implementation was possible due to the use of simulation within the FD process. The manufacturer of the CH147F built a Systems Integration Laboratory (SIL) that provided a virtual simulation of the CH147F cockpit technology. It was used to refine specifications, allowed the introduction of technology that was not available at contract award, and allowed testing of the mission systems on the ground without concerns of fuel, weather, or aircraft serviceability. An estimated 90% of the flight test was completed as a ground test before the aircraft was built. Additionally, a flight dynamics model of the CH147F was used to predict handling qualities of the aircraft before flight assessment by the Experimental

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[127] Stahlkocher, 'Piasecki H-21', Wikipedia. The Free Encyclopedia, 2005, https://commons.wikimedia.org/w/index.php?curid=266474.

[128] 'CH-113 Labrador - Canadian H-46s for the Modeler', CdnSARLab Blog, 1 February 2014, http://cdnsarlab.blogspot.com/2014/02/cockpit-details.html.

[129] Jorge Gazzola, 'Bell CH-146 Griffon', Helicopter History Site, 1997, https://www.helis.com/database/model/CH-146-Griffon/photos.

[130] Sven Zimmerman, 'CH-149 Cormorant', Airfighters.Com, 2002, https://www.airfighters.com/photo/90963/M/Canada-Air-Force/AugustaWestland-Mk511-CH-149-Cormorant/149912/.

[131] Jorge Gazzola, 'CH-147F First CAAS Cockpit', Helicopter History Site, 7 October 2013, https://www.helis.com/database/news/ch-47f_cockpit.

[132] Daghir et al., 'CH147F Crew Stations Interface Document'.

Test Pilots.[133] This was only completed for tests that provided engineering data and not pilot judgement, yet allowed the optimization of the flight model before flight test, resulting in fewer changes and less need for re-test.

Full Operational Capability for the CH147F was delayed as many of the advanced systems required test and evaluation at special test facilities that have low availability. The electronic warfare defences could have been tested in part if the SIL had a pilot model of suitable integrity and it could be integrated with the Virtual Proving Ground (see Chapter 5), allowing an understanding of the defences without waiting for the special test facilities and possibly reducing the time needed at those facilities. With the inclusion of a pilot model of sufficient fidelity, the SIL could fly many different routes and altitudes in a threat environment to find the safest way to complete a mission. With sufficient hardware performance, this could shorten the tactics development time within the FD effort.

To illustrate the effect of first the introduction of technology and then the effect of constructive simulation to ease FD efforts, a real project example is not possible. There is no project that has been repeated under three different technology levels but was otherwise identical. Instead, consider an arbitrary project that historically would have taken seven years to complete. This is broken down into the five procurement stages and three operational tasks within FD at Figure 3.4, with historic timelines in blue. Introducing technology has two main effects on FD: each phase is more complex so can take longer and the Operational Development activities need to be delayed until the new technology is available. By adding six months to six of the eight stages, delaying the

[133] Colosi et al., 'ADS-33 Evaluation of the International CH-47 Chinook'.

operational development, and conservatively doubling the time required to complete training due to more training required with fewer resources, the arbitrary project takes an additional five and a half years. This is shown in red in Figure 3.4.

With a constructive simulation capability established, defining the requirements and comparing options could be reduced by modelling the proposed specifications and then executing the models to confirm their validity. The definition phase is primarily an administrative process, but it is faster when requirements are rigorous and do not need rewriting. The implementation phase is potentially reduced in that rigorous initial requirements prevent some of the re-writing of requirements that slows build times. The implementation phase also includes the test and evaluation of the new product, which could be reduced by evaluating modelled systems. Operational development activities are similarly reduced, plus they can begin early in implementation once accurate models are developed rather than waiting for live aircraft to be delivered. The training is strongly affected by simulation, as the use of virtual simulators will shorten training times. Also, with constructive simulation providing CGF as adversaries and for friendly interoperability training, more missions can be trained virtually so the use of simulators for training can be vastly increased and training times further shortened. These effects are shown in green in Figure 3.4 with the arbitrary project timeline shortening to eight years.

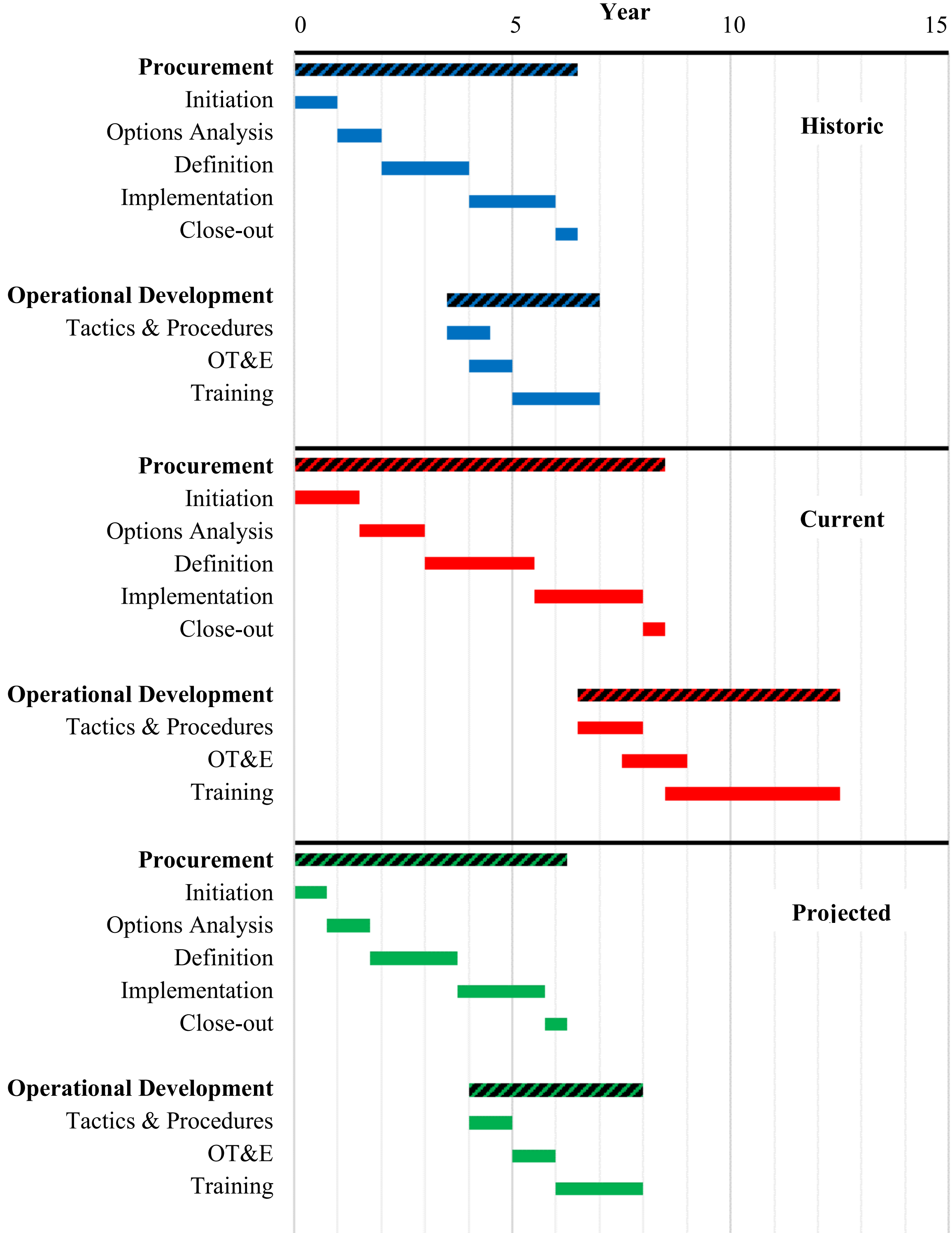

Figure 3.4 - Duration of an Arbitrary Capability Development Project[134]

As discussed in the above text, Figure 3.4 is only an example of timelines of an arbitrary capability development project. It includes a historical timeline that shows how projects were completed relatively quickly in the past, a current timeline that shows effects throughout the FD processes that lead to extensive project delays, and a projected timeline that demonstrates the potential effect of using constructive simulation to address the complexities introduced with the emerging technologies.

Force Generation

FG is the next organizational function where a constructive simulation capability can reduce complexity. This function includes developing personnel, developing tactics, and ensuring equipment readiness. When using a virtual simulation to train personnel, the inclusion of advanced CGF from a constructive simulation expands the extent of the training where multi-aircraft missions can be flown with a single human crew. Tactics development can use the virtual simulation to confirm the optimized solutions identified during FD.

The FG task of ensuring readiness of the equipment is supported with constructive simulation reducing demand on the actual aircraft. When aircraft are not used for training or tactics development, their availability for missions could increase. This point is admittedly weak as the reduced demand on the aircraft would likely result in reduced numbers being procured or reduced resources being assigned to maintaining readiness. However, there still is strength in that benefit as it aligns well with the GoC expectation of being efficient with resources and the SSE Initiative #101, "Reduce greenhouse gas emissions by 40 percent from the 2005 levels by 2030."[135]

[134] Illustrative data created by the author.
[135] Canada. Department of National Defence, Strong, Secure, Engaged - Canada's Defence Policy., 76.

Force Employment

FE is the final organizational function that demonstrates constructive simulation's ability to reduce complexity. Central to FE is a planning process that coordinates capabilities to "proceed at the optimal place and time with minimal prohibitive air interference."[136] Planning may be conducted with the CAF's Operational Planning Process (OPP) where the purpose is "to determine the best method of achieving the desired end state in support of strategic guidance."[137] OPP is limited in that it is personnel-intensive and can only select the best method from the few methods that are manually developed over days. Wargaming is a process within OPP to challenge a proposed method and can use simulation but is still limited to evaluate a small number of methods. Similar to the Monte Carlo simulation example in Chapter 1 where the departure time and route from work to home are optimized, it would be possible to optimize at least portions of an operational plan by describing bounds and simulating many choices within those bounds.

There will be situations where speed in determining a sufficient solution vice awaiting an optimized solution would best support FE. For example, for an OP LENTUS mission to support a large community threatened by a forest fire (e.g. the Fort MacMurray fire in May 2016[138]) a rapid helicopter evacuation of civilians may be required. A constructive simulation could optimize the number and the locations of evacuation sites to use, with considerations for road closures due to fire danger, to

[136] Canada. Department of National Defence, Canadian Forces Joint Publication: CFJP 3.0: Operations (Ottawa: Canadian Forces Experimentation Centre, 2010), 1–4, http://epe.lac-bac.gc.ca/100/200/301/dnd-mdn/cdn_forces_joint_publication-ef/D2-252-300-2010-eng.pdf.

[137] Ibid., 5–2.

[138] Canada. Department of National Defence, 'Operation LENTUS - Canada.Ca', Government of Canada, 11 December 2018, https://www.canada.ca/en/department-national-defence/services/operations/military-operations/current-operations/operation-lentus.html.

minimize the risk to civilians and the time to evacuate. A greater simulation speed could mean more possibilities are tested and results could be determined earlier. This scenario also shows value in providing constructive simulation support to deployed operations, which may be a suitable high-level requirement for the capability.

CONCLUSION

The GoC has indicated where they expect DND to be headed using SSE. The RCAF has been unable to demonstrate progress in all its new complex aircraft acquisition projects and the available reports suggest this progress is behind the GoC's projections. By demonstrating the potential effects of a constructive simulation capability and by using some real examples and an arbitrary project timeline, the potential for constructive simulation to enhance the RCAF's FD, FG, and FE was demonstrated. The viability of this capability within SSE was demonstrated by showing alignment with at least four of the initiatives.

This chapter demonstrates the constructive simulation capability as a means to address complexity in airpower that is consistent with departmental priorities. Next, a look at milestones in simulation will demonstrate that technology has sufficiently grown to support this capability. Also, the increasing use of simulation within these milestones will indicate increasing acceptance of simulation by the RCAF.

CHAPTER 4. MILESTONES IN SIMULATION

Simulation is a very broad term and a very broad field. It includes any use of a model over time to replicate a real object or process. The use of wooden sticks and target circles to practice swordsmanship and archery is very much a form of live simulation. The two-thousand-year-old mechanical tools that modelled the motion of celestial objects, such as the *Antikythera mechanism*,[139] were constructive simulations. More recently, the use of personal computers to replicate an interactive environment whether for instruction, development, or even gaming is a virtual simulation. The growth of these broadly defined simulations has not been a continuous process from archery practice to virtual reality gaming. Instead, it has been a series of step changes that provide insight into the readiness for further simulation developments.

Many of the step changes in simulation occur either due to a technological breakthrough or due to an external change that increased the need or value of the simulation. Simulation milestones in either aerospace or RCAF history provide lessons that should be considered during the transition to a robust constructive simulation capability. This chapter will review some of the influential RCAF, aerospace, and technology milestones and will relate them to considerations in developing a robust constructive simulation capability.

This use of simulation has primarily been in the virtual simulation domain, and even there it has almost exclusively been for training, allowing optimized conditions for learning and greatly reducing the risk inherent in training. Fortunately, the widespread

[139] T. Freeth et al., 'Decoding the Ancient Greek Astronomical Calculator Known as the Antikythera Mechanism', Nature 444, no. 7119 (November 2006): 587–91, doi:10.1038/nature05357.

use of simulation has also generated some resources and affected some attitudes that will help the development of a robust constructive simulation capability for the RCAF.

A brief history of simulation in the RCAF will show the increasing use and reliance on simulation. That will lead to an examination of the uses of simulation within the RCAF and will identify many of the resources that will help enable the development of a constructive simulation capability. As with many modern technologies, there are non-widespread as well as emerging uses of simulation that, as they develop further, will also contribute to the development of a constructive simulation capability. A review of some of the future simulation uses in the RCAF will identify these additional developments.

1939 – The Link Trainer

The Canadian Prime Minister, William Lyon Mackenzie King, determined that "the most essential military action that Canada could undertake"[140] in support of World War II was the British Commonwealth Air Training Program (BCATP). The BCATP trained pilots from across the Allied nations to fight in the air battle. Canada was an ideal location for several reasons, but still found challenges in developing the skills pilots needed to operate aircraft on instruments, without seeing the ground or the horizon. They needed to wait for appropriate weather conditions, they needed to add flying time to the training program when resources were already scarce, and they needed to accept the risk of crashing due to disorientation. These *instrument flying* skills could be taught on the Link Trainer, Canada's first flight simulator.

[140] Canada. Veterans Affairs, 'The British Commonwealth Air Training Plan', Government of Canada, 14 February 2019, https://www.veterans.gc.ca/eng/remembrance/history/second-world-war/british-commonwealth-air-training-plan.

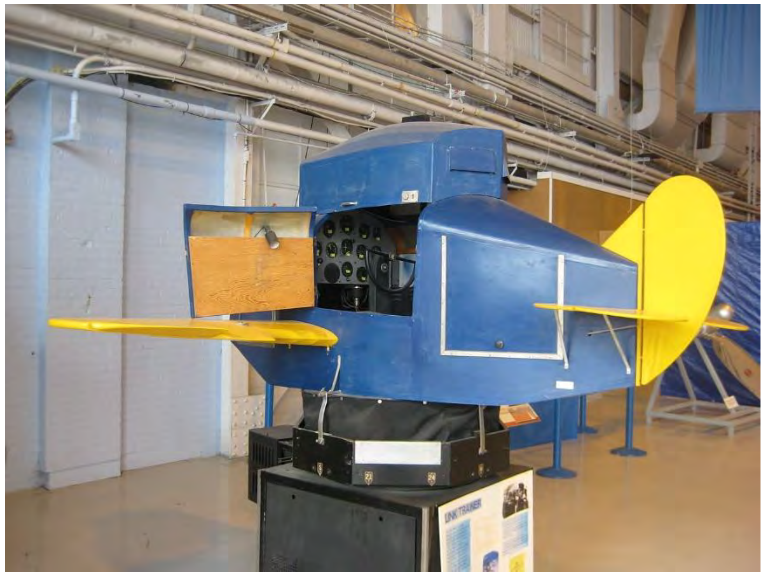

Figure 4.1 – Link Trainer at the Western Canada Aviation Museum[141]

The Link Trainer (Figure 4.1) was selected by the RCAF in 1939. A few models are still in use at museums and cadet organizations. It provided an environment that helped to develop instrument flying skills. It was a model of a cockpit with working instruments and could replicate the motion of an aircraft in response to the pilot's control inputs. The low production and operating cost allowed extensive use of the trainer. It eliminated concerns of weather limitations and crashing. The Link Trainer reduced the complexity of aerospace training.

The Link Trainer and other more primitive simulations were available before BCATP but none was selected by the RCAF until experiencing the demands of training thousands of pilots. This is a case where a step-change in the use of aerospace simulation occurred due to external pressure. Since World War II, the demand for pilot training has never returned to the levels seen by the BCATP but the use of simulation in pilot training

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[141] Western Canada Aviation Museum, 'Link Trainer', Wikipedia. The Free Encyclopedia, accessed 1 May 2021, https://en.wikipedia.org/wiki/Link_Trainer.

has continued to advance. Once it was accepted as a viable method, the only justification necessary to continue its use was the value of the simulation.

1957-1970 – Training Command

After World War II, the RCAF reduced its size from 215,000 personnel to a 16,000-person peacetime strength. However, after joining the North Atlantic Treaty Organization (NATO) in 1949 and then establishing the North American Air Defence Command (NORAD) in 1957, the RCAF grew to approximately 54,000 personnel. During this period, the first helicopters were introduced, a new fleet of CF101 Voodoo air defence fighters and a new fleet of CF104 Starfighter strike/reconnaissance fighters were procured. The growth of the RCAF and the new aircraft required a surge in training that was addressed in 1957 by establishing a Training Command in the RCAF. Although various training simulators were available for some of the aircraft, the use of simulation does not appear prominently in the historical records. John Corrigan's book *The Red Knight*[142] includes a first-hand record of Training Command by Lieutenant-Colonel Jack Waters, an instructor pilot and a leader in the command. He discussed the organization of Training Command, the training progression of new pilots, the units and locations used for training, and the aircraft used as trainers throughout this period. There was no mention of simulators in *The Red Knight*.

This lack of information represents an important era in simulation because it demonstrates a low level of buy-in to simulation that contrasts with the BCATP use of simulation. The Link Trainer was incorporated as a necessity to deal with the wartime training surge. Twenty-five years after that surge, the available simulation would have

[142] Corrigan, The Red Knight.

been much more capable, but without the demand, it became an alternate training method vice an essential tool.

1963-1967 – NASA's Lifting Body Aircraft

The post-war development of aerospace capabilities in the United States led by the National Advisory Committee for Aeronautics (NACA), which became the National Aeronautics and Space Administration (NASA), provided many technological breakthroughs that enabled advancement in simulation.

NASA had many ideas for a controlled return from space that resulted in the design of the Space Shuttle. Early testbeds for the Space Shuttle were the so-called Lifting Bodies. These were aircraft without wings or engines, where the body produced small amounts of lift and large amounts of drag. Control surfaces allowed manoeuvring of the rapidly descending Lifting Body aircraft to a controlled landing. Larry Taylor was an engineer studying pilot-control problems who "claimed he could use mathematics to describe the piloting characteristic of a test pilot, then predict the outcome of a planned flight."[143] He completed a stability analysis and determined regimes where the aircraft would encounter stability issues.

[143] Reed and Lister, Wingless Flight: The Lifting Body Story, 25.

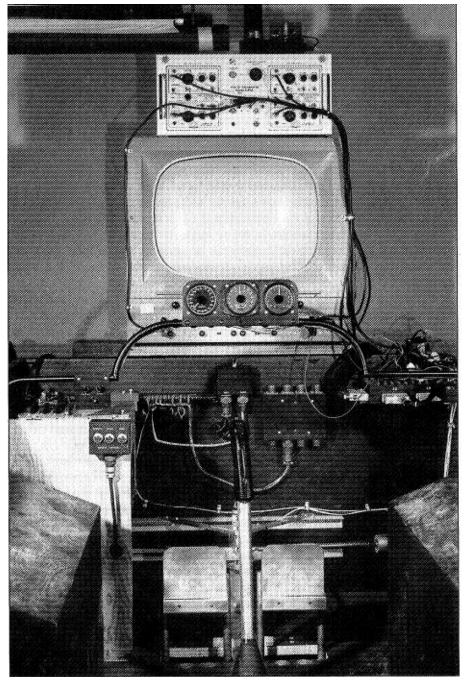

Figure 4.2 – The Lifting Body Aircraft Simulator[144]

In 1963 Bertha Ryan and Harriet Smith,[145] two junior NASA engineers with no experience in simulation, built a very simple simulator that had similar flight controls as the aircraft and could display a horizon line and a heading pointer on a screen (see Figure 4.2). Taylor's stability analysis provided numeric parameters that were manually programmed using 30 or 40 rotary knobs,[146] which required that each flight in the simulator start with verification and validation of the flight model.

For the test pilots to learn to fly these aircraft, the simulator was necessary. A flight of a Lifting Body aircraft lasted approximately four minutes from its high-altitude release from the wing of a large aircraft, completion of one or two test manoeuvres, then

144 Ibid., 30.

145 Reed and Lister, Wingless Flight: The Lifting Body Story: 1997. Reed and Lister observed that Bertha Ryan and Harriet Smith were perhaps the first "all-woman simulation teams" and were very successful despite "neither of them [having] ever set up a flight simulator before"

146 Reed and Lister, Wingless Flight: The Lifting Body Story, 29.

set up and complete a landing. The unconventional configuration prevented mission rehearsal in similar types.

The simulator first provided important effects in 1964 when used to aid in the design of the aircraft. Test Pilot Milton Thompson identified that the control surfaces required unusual steering techniques so he evaluated different control configurations in the simulator, and recommended a configuration that opposed the norm but was more intuitive.[147] It next proved its value on 10 May 1967 when Bruce Peterson, a test pilot flying the M2-F2 Lifting Body, encountered a stability problem that put the aircraft well outside its planned flight. Although only his third flight in that model of aircraft, he was able to regain control and bring the aircraft to a controlled but hard landing, which unfortunately caused a landing gear to collapse and severe injuries to the pilot.[148] Peterson's recovery from the unstable flight and successful landing were a result of his deep understanding of the controls that came from the simulator training.

This story was a vignette that represents some important milestones in aerospace simulation. First, Taylor used an analysis of the design to generate a flight model rather than using data from a flight test. Second, the aircraft design process used the simulator. Third, the test pilots used a simulator for initial training on a new type. Earlier uses of simulation were as a supplement to flight training, not as a precursor. Finally, Taylor's notion of building a mathematical model of a pilot was at the start of a movement within control engineering that had led to an ability to create constructive simulations of piloted aircraft.

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[147] Hans-Jürgen Becker, Nasa, Space Flight Research and Pioneering Developments (Atglen, PA: Schiffer Pub, 2011), 91.

[148] The story and video of the crash of one of the lifting bodies, aircraft M2-F2 was used in the opening sequence of the 1974 television series, "The Six Million Dollar Man"

1966 – Apollo Lunar Mission Simulator

Simulators were used throughout the US space program, from large motion-replicating lunar landers to computer-based simulations that provided a real-time reproduction of the systems in the different space vehicles. While the technology in the simulations was at the forefront of computer capabilities, the extent of the simulation as a training tool was the most remarkable advance, with "each crewman in the Mercury, Gemini, and Apollo programs [spending] one third or more of his total training time in simulators [and] lunar landing crews [using] simulators more than half the time."[149]

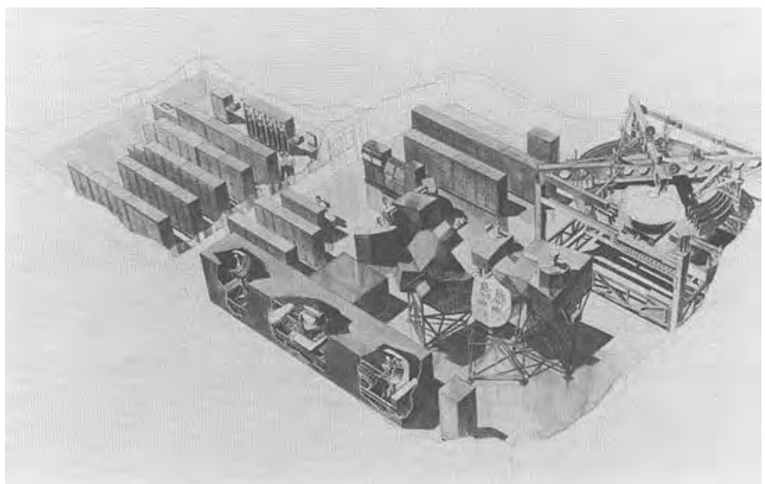

Figure 4.3 – The Apollo Lunar Mission Simulator[150]

Perhaps the most advanced simulator was the Apollo Lunar Mission Simulator (Figure 4.3) as it supported three crew members conducting the most complex manoeuvres in space flight at the time, including the operation of all control, navigation, electrical and life support systems for a mission that was to be self-sustained for as long

[149] Tomayko, Computers in Spaceflight: The NASA Experience, chaps 9–2.
[150] Tomayko, Computers in Spaceflight: The NASA Experience.

as 13 days.[151] The simulated lunar module, the operator stations, and the computer banks could have filled a gymnasium. It provided almost 30,000 hours of training in its five years of active use and is still functioning today.[152] The high fidelity of the network allowed engineers to devise a power-saving scheme to recover the Apollo 13 crew after an onboard explosion and loss of oxygen and fuel reserves. NASA engineers used the simulator to develop procedures "in three days, instead of the usual three months,"[153] demonstrating the use of simulation in support of tactics development during FE.

The development of space flight models is also an important milestone in simulation. It occurred for two main reasons. First, there was no option. Spaceflight had not been done yet and the only way to train would have to be a simulated environment. Second, it was relatively easy. Physicists jokingly refer to "spherical cows" to represent problems that are solvable only after simplifications such as assuming there is no air resistance.[154] Spaceflight, to physicists, is a spherical cow. There is no air resistance, the forces are very predictable, and gravity does not vary considerably when far from the earth's surface. The fact that the relatively simple equations would be accurate without spherical cow simplifications guaranteed that high fidelity simulators could be built. This guarantee helped garner support in the development of greater hardware capabilities. In Chapter 6, this interaction between the model and the hardware will be presented as a very important consideration in the development of a constructive simulation capability.

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[151] Brian Dunbar, 'Apollo Missions', NASA, 2017, https://www.nasa.gov/specials/apollo50th/missions.html.

[152] 'Apollo's Lunar Module Simulator', Apollo11Space, 2021, https://apollo11space.com/apollos-lunar-module-simulator/.

[153] Brian Dunbar, 'Apollo 13 | NASA', NASA, accessed 1 May 2021, https://www.nasa.gov/mission_pages/apollo/missions/apollo13.html.

[154] John Harte, Consider a Spherical Cow: A Course in Environmental Problem Solving, Nachdr. (Sausalito, Calif: Univ. Science Books, 1988).

1969 – The Differential Maneuvring Simulator (DMS)

Following the air wars in Korea and then in Vietnam, US defence scientists were interested in understanding theories of air combat. Following the success of various methods of simulating air combat for a pilot in a simulator, the Differential Manuevring Simulator (DMS) was developed. The DMS allowed two pilots to fly simulated combat in the same simulated environment, either working together or as adversaries. The DMS was a success as a training simulation where US Navy and US Air Force pilots "all considered the simulator runs extremely beneficial in improving their flying techniques."[155] Also, Al Meintel, a defence scientist who was struggling with the mathematical challenge of solving air combat problems was able to develop air combat rules from his analysis of DMS experiments.[156]

The DMS is a simulation milestone in that it developed technologies that are still of value today (e.g., networked simulation, air combat models), it demonstrated value in the use of simulation for tactics development, and the agreement of its value by the many pilots using DMS to train in air combat demonstrates strong buy-in for use in training difficult missions.

1960s – An Investment in Simulation

The preceding three developments in simulation all came from NASA when the US was advancing aerospace in support of the Cold War and the Space Race. The increased use of simulation was a result of the huge effort and spending in developing new technologies. The budget of NASA, both as a percentage of the US Federal Budget

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155 Phillips, 'Journey Into Space Research', 63.
156 Ibid., 61.

and in dollars corrected to their value in the year 2019, is shown in Figure 4.4. The budget peak in the years preceding the NASA developments[157] demonstrates an important aspect of the support required to generate technological breakthroughs. This support was supported politically due to the threats of the Cold War and the desire to succeed in the US-Soviet Space Race. Because of changes in the global situation, this level of support to aerospace or simulation research and development is not expected to come from the Canadian or the US governments in the foreseeable future.

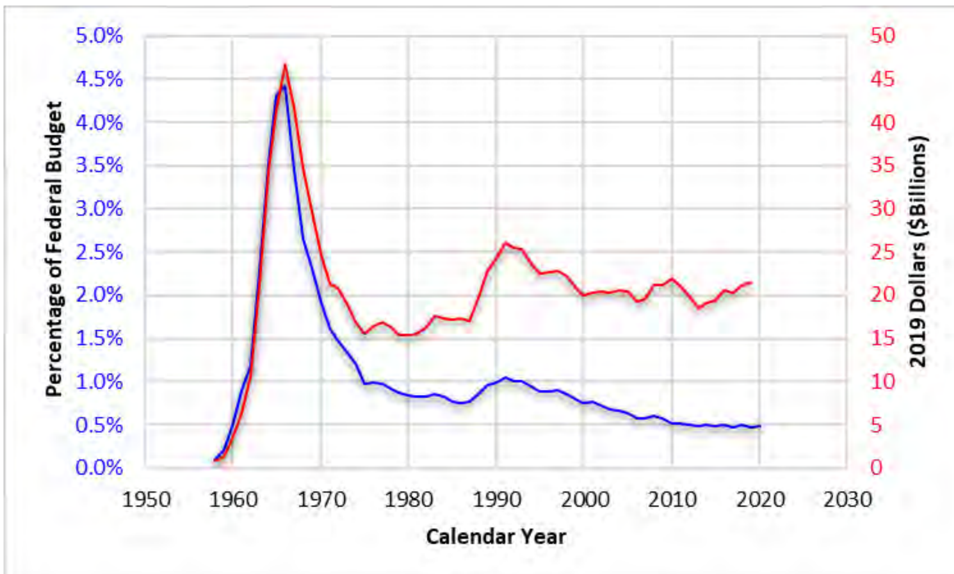

Figure 4.4 – NASA Budget as a Percentage of US Federal Budget[158]

The development of simulator technology demonstrated by NASA was unquestioningly valuable to aerospace R&D, but it comes at a cost. The 1960s spending spike shown in Figure 4.4 covered the incredible pace of space missions and aircraft development that included the preceding advances in simulation.

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157 'Budget of NASA', Wikipedia. The Free Encyclopedia, 25 February 2021, https://en.wikipedia.org/wiki/Budget_of_NASA.

158 Ibid.

1979 – Microsoft Flight Simulator

The experiences of using physics to develop flight models and the relatively high-speed computers that became available for home users allowed the development of what was the most common aerospace simulation for many years. Sold as a game, it was not approved for training but was effective for practice and maintenance of skills even with the rudimentary displays originally generated (see Figure 4.5). The extremely low cost of this simulator made a flight simulator a common tool for many pilots and flight schools. This increased buy-in merely by reaching so many people. Additionally, the low cost allowed MSFS to be upgraded as computer hardware and software technologies permitted.

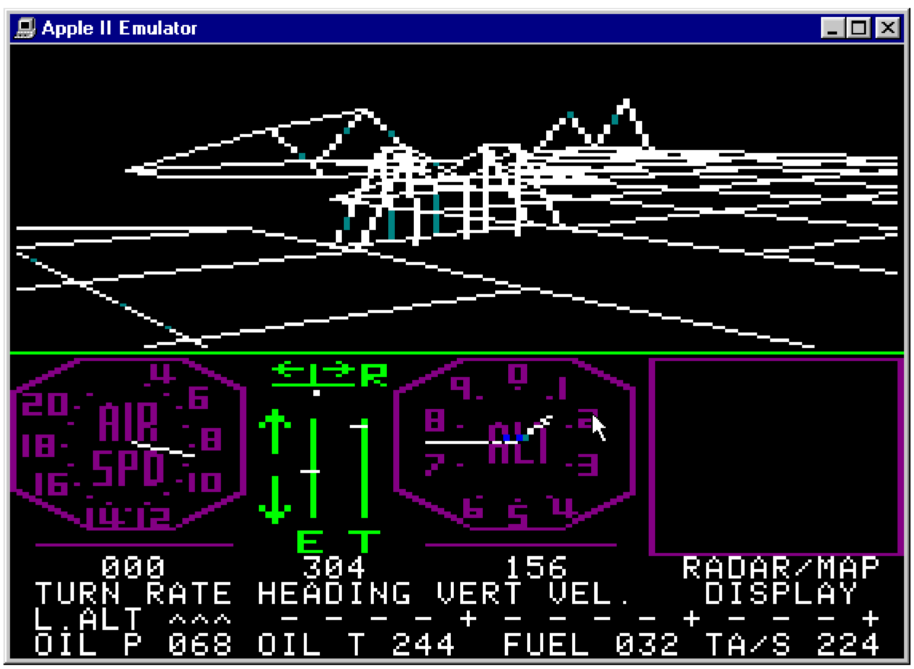

Figure 4.5 – Screenshot from PC Flight Simulator in 1979[159]

[159] Jos Grupping, 'Flight Simulator History', FlightSim Greenland, 24 June 2016, https://flightsim.gl/flight-simulator-history/.

1970s & 1980s – Change for the RCAF

The unification of the three branches of Canada's military in 1968 started an era of change to the RCAF (Air Command at the time, but for clarity one term is used throughout). During the 1970s the RCAF operated at least 44 different aircraft types, which included 7 types that were introduced and 12 types that were retired in that decade.[160] They were working towards procurement of 5 more types to become operational in the 1980s. For comparison, the RCAF of 2021 operates 23 aircraft types including three procured in the last decade. Each type required a training plan and resources. Each retirement of a type required retraining all the aircrew. This large change in the RCAF fleet that created a large training demand was an external factor for which simulation was part of the solution.

The 1970s is not a good example of effective use of simulation by the RCAF. Most of the training was conducted on the actual aircraft, justifying realism over simulation, perhaps influenced by General George S. Patton's popular quote "you fight like you train." However, the attitude to simulation was changing. The technological breakthroughs, many by CAE, a Canadian company closely associated with the RCAF,[161] plus the massive training effort that arose from the large changes in the RCAF fleet did set the stage for procurement of training simulator capabilities for every fleet over the next 20 years. Attitudes are not well documented in the historical record, but it seems that early in the 1970s, the value of simulation or perhaps the 'buy-in' was not strong enough in the RCAF to warrant extensive use. By the end of the 1980s simulation was in regular use throughout the RCAF, and modern procurement such as the CP140 Aurora

[160] Canada. Department of National Defence, 'Royal Canadian Air Force History'.
[161] CAE Inc., 'About CAE - History'.

maritime patrol aircraft[162] and the CF18 Hornet fighter[163] were delivered with extensive flight and mission simulation capabilities.

1990s Simulation Requirements

The 1990s saw the development of a strong air force identity. The many capability groups who each managed group flying orders and training requirements were brought together to develop one set of RCAF orders. A strong focus in Flight Safety to eliminate human cause factors from accidents had resulted in safe training practices where some essential training was no longer permitted on the aircraft and must be conducted periodically by each aircrew member in a simulator. Aircraft fleets that did not have a simulator arranged the use of foreign military or commercial simulators. The use of training simulators increased because of a demand for more rigorous training, and the ability for training simulators to provide better training in certain areas.

2014 RCAF Simulation Strategy

The trend of increased use of simulation continued in the new millennium with numerous developments, but few significant milestones until in 2014 when the buy-in of simulation for the RCAF was detailed in full clarity with the release by the Commander of the RCAF in the *RCAF Simulation Strategy*[164] (RSS). This document acknowledged the benefits of simulation, identified future uses of simulation (including constructive simulation), and challenged fleets to maximize the use of simulation in the training of the personnel. Unfortunately, the procurement in the RSS was costly and did not align with

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[162] Ernie Cable, 'CP140 Aurora Beginnings', Warrior, The Shearwater Aviation Museum Foundation Magazine, 2009, http://jproc.ca/rrp/rrp3/cp140_beginnings.html.

[163] T. Leversedge, 'McDonnell Douglas CF-188B Hornet' (Canada Aviation and Space Museum, 2013), 8, http://documents.techno-science.ca/documents/CASM-Aircrafthistories-CF-18Hornet.pdf.

[164] Canada. Department of National Defence, RCAF Simulation Strategy 2025.

higher procurement priorities. The RSS became a guidance document and not a plan that was implemented.

2020 – Microsoft Flight Simulator

The continual advancement of computer capabilities is evident in a still image of Microsoft Flight Simulator, 41 years after initially released. Compare Figure 4.4 with Figure 4.5. The horizon line and terrain drawn with empty polygons are replaced with photo-realistic scenery. Although not evident in a still image, the advances in the flight dynamics models, networked simulation, and CGF developed in parallel with the graphics quality. Many PC-based simulations can now be certified by civilian aviation agencies as a training device.[165]

The simulation milestone represented by this release of the software is the change from simulated environment to photo-realistic environment. The advancement of all components is represented by this visual change, suggesting the high fidelity that can be developed for other models. The simplicity of 'suspending disbelief' when 'flying' in the scene in Figure 4.6 may sway all those who still question the buy-in of simulation.

[165] Canada. Transport Canada, TP9685E Aeroplane and Rotorcraft Simulator Manual, Revision 3, 2005, https://tc.canada.ca/en/aviation/publications/aeroplane-rotorcraft-simulator-manual-tp-9685.

Figure 4.6 – Screenshot from Microsoft Flight Simulator 2020[166]

CONCLUSION

Since the Link Trainer was used to support the BCATP, simulation has been a part of aerospace and a part of the RCAF. The preference to use simulation started with need, then became a niche training capability, and by the 1990's it was increasing flight safety by enhancing essential training. Throughout this period the technology has advanced from the mechanical Link Trainer, to the development of digital computing solutions in support of NASA projects, to a home PC simulation that can suspend reality and provide qualified training. The growth in the RCAF has followed technology but with a buy-in to the value of simulation that started slow but has grown to the extent that the Commander has ordered the use of simulation. This technology, buy-in, and doctrinal support create an environment that will be accepting of the development of a constructive simulation capability.

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[166] Cecilia D'Anastasio, 'The Uncanny Escapism of 'Flight Simulator 2020', WIRED, 21 August 2020, https://www.wired.com/story/flight-simulator-2020-uncanny-escapism/.

The next consideration to determine whether the RCAF should develop a constructive simulation capability is to identify the existing capabilities. Those capabilities may have elements that can support constructive simulation, plus the existing capabilities will give further insight into the buy-in of simulation.

CHAPTER 5. RCAF AND SIMULATION

The RCAF's increased buy-in of simulation has brought it to the current situation where, in 2014, the RCAF Commander shared a vision that "by 2025, the RCAF will have a simulation-focused training system which skilfully leverages live, virtual, and constructive domains."[167] That vision was shared in the publication RCAF Simulation Strategy 2025 (RSS) which outlines many of the capabilities discussed in this paper. Unfortunately, the RSS maintained a training simulation focus with an acknowledgement that non-training benefits may develop over time. Also, implementation of the RSS was delayed indefinitely as it didn't directly align with specific departmental goals, hence the Chapter 3 focus on alignment with SSE initiatives. Although this training focus is evident in the holistic use of simulation in the RCAF, there have already been developments of niche capabilities that use simulation in other ways.

The following chapter presents the primary uses of simulation in the RCAF, the inventory of RCAF simulators, organizations that use simulation, and RCAF partners who have simulation capabilities that may be supportive of the development of a constructive simulation capability. This awareness is important for the constructive simulation capability as elements of existing simulations may be transportable and the extent of simulation use and knowledge further demonstrates the buy-in to simulation.

USES OF SIMULATION

The term *training simulators* includes a large variety of devices with a large variety of capabilities and levels of fidelity. Each simulator is unique, developed to train

[167] Canada. Department of National Defence, RCAF Simulation Strategy 2025, xiii.

and assess a particular set of tasks. There are four main categories: full flight simulator (FFS), flight training device (FTD), rear crew trainer, and maintenance trainer. Each may be further described by its training role: flight, mission, or procedural. For example, landing the aircraft would be flight training, locating a submarine would be mission training,[168] and practicing emergency responses would be procedure training.[169] FFS's and FTD's are very similar except FFS's simulate the motion of an aircraft, allowing training of skills that respond to motion cues and assisting with the *suspension of disbelief*.[170] A full mission simulator would be an FFS that also models the mission essential equipment and environment. The rear crew trainers and the maintenance trainers are built with a similar level of technology and for the same spectrum of training, but for different crew positions.

The importance of the diversity in training simulators is that it represents different configurations of the same simulant, each optimized for a particular training function, and thus may be developed using different component models. The diversity of models is an important resource when developing a constructive simulation and will be discussed in Chapter 6.

Mission rehearsal is a simulator capability that is closely related to training in that full crews would use simulators to fly a mission in an environment that may not be available to the aircraft. If a fixed-wing aircraft is deploying to a winter location, they could rehearse landings on snow- and ice-covered runways.[171] If a helicopter squadron

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[168] John F. Schank and Rand Corporation, eds., Finding the Right Balance: Simulator and Live Training for Navy Units (Santa Monica, CA: Rand, 2002), 141.

[169] John W. Jacobs et al., 'A Meta-Analysis of the Flight Simulator Training Research': (Fort Belvoir, VA: Defense Technical Information Center, 1 August 1990), 17, doi:10.21236/ADA228733.

[170] Marfelt, 'The Holy Grail of Virtual Reality (VR): A Complete Suspension of Disbelief'.

[171] Edward Martin, 'Guidance for Development of a Flight Simulator Specification' (Wright-Patterson AFB, Ohio: Air Force Research Laboratory, May 2007).

will be supporting operations in mountainous areas, they could rehearse mountain flying skills and navigation, provided the terrain model is suitable.[172]

Capability development is a powerful use of simulators where the procedures and tactics of a new type of flying could be developed and rehearsed in a simulator. Landing a large aircraft on a small gravel runway may require a different landing technique flown at lower speeds that may be dangerous to try in the aircraft. The success of this depends on the fidelity of the models. If the aircraft performance close to the ground at lower speeds is not accurate, then the procedure may be invalid for use in the actual aircraft.[173] Capability development in simulators can also be used for product development such as optimizing hardware and images used in a new helmet-mounted display[174] where multiple users can assess the displays, rapid changes can occur without cumbersome airworthiness processes, and flight risk with new equipment is eliminated.

CURRENT RCAF CAPABILITIES

The RCAF uses simulation throughout its operations, primarily as virtual simulators used for training and some mission rehearsal. There is a small amount of constructive simulation completed in support of RCAF that demonstrates value in constructive simulation and may also be supportive of a future RCAF constructive simulation capability.

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[172] Michael E McCauley, 'Do Army Helicopter Training Simulators Need Motion Bases' (Arlington, VA: US Army Research Institute for the Behavioral and Social Sciences, February 2006).

[173] Advisory Group for Aerospace Research and Development, 'The Aerodynamics Ofo V/STOL Aircraft', AGARDograph 126 (May 1968): 498.

[174] Sudesh K Kashyap, 'Development of HUD Symbology for Enhanced Vision System', Journal of Aerospace Sciences & Technologies 69, no. 1 (n.d.): 13.

Virtual Simulators

The RCAF operates 23 different types of aircraft[175] and provides simulator training on 21 of those types[176] using at least 75 RCAF-operated training simulators and 12 simulators operated by other government departments.[177] Table 5-1 lists the simulators by RCAF capability group and aircraft type.

The RCAF has developed simulation capabilities beyond trainers. For example, the Mission Rehearsal Tactical Trainer (MRTT) is a CH146 Griffon helicopter simulator[178] intentionally built with a low fidelity flying model, no motion, and with the analog instrument panel (Figure 3.3) recreated on a computer monitor (Figure 5.1). An MRTT allows a full crew to rehearse multi-aircraft mission procedures, in a network of six other MRTT's across Canada.

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[175] Canada. Department of National Defence, 'RCAF Aircraft', Government of Canada, 3 March 2021, http://www.rcaf-arc.forces.gc.ca/en/aircraft.page.

[176] The 61-year-old CT-114 Tutor aircraft is used by 431 Air Demonstration Squadron, and the 57-year-old CC115 Buffalo is used by 442 Search and Rescue Squadron.

[177] FlightGlobal and CAE, 'Military Simulator Census 2020'.

[178] Canada. Department of National Defence, 'Simulators and Trainers'.

Figure 5.1 - CH146 Griffon Mission Rehearsal Tactical Trainer[179]

That network was expanded into the *CFXNet* which can link simulators that use a standard simulator network communication method into one multi-aircraft training simulation. The Aerospace Environment Controllers that track aircraft on radar and coordinate an intercept of unidentified aircraft can learn and rehearse their skills on the *Battle Control System-Fixed* simulator,[180] which can also be networked through the CFXNet.[181]

[179] The ADGA Group, 'Modelling and Simulation: MRTT Case Study', ADGA Group, 2019, https://www.adga.ca/adga-defence/modelling-and-simulation/.

[180] M. Bélanger et al., 'Building a RAP from an R&D Perspective' (Valcartier: Defence R&D Canada, June 2007).

[181] Craig Jorgenson, 'M&S Course Questions', email to author, 8 April 2021.

Table 5-1. RCAF Current Inventory of Simulators[182]

Capability	Aircraft Type	Number	Simulator Type
Training	King Air	1	Full Flight Simulator
	Bell 206	1	Flight Training Device
	Bell 412	1	Full Flight Simulator
		1	Flight Training Device
	BAE Hawk	2	Flight Training Device
	T-6 Texan	3	Flight Training Device
Fighter	CF188 Hornet	6	Part Task Trainer
		4	Tactical Trainer
		6	Tactical Operational Flight Trainer
Maritime Helicopter	CH148 Cyclone	6	Mission Procedure Trainer
		2	Full Flight Simulator
Maritime Patrol	CP140 Aurora	1	Full Mission Simulator
		1	Operational Flight Trainer
		2	Operational Mission Simulator
		3	Rear Crew Trainer
		1	Full Flight Simulator
		1	Flight Training Device
Search and Rescue	CC295 Kingfisher	1	Cockpit Procedure Trainer
		1	Full Flight Simulator
		8	Mission Procedure Trainer
		1	Operational Mission Simulator
		1	Part Task Trainer
		1	Sensor Simulator
		1	Virtual Maintenance Trainer
	CH149 Cormorant	1	Cockpit Procedures Trainer
	CC130H Hercules	1	Full Flight Simulator
Tactical Aviation	CH146 Griffon	1	Full Mission Simulator
	CH147F Chinook	1	Deployable Tactical Flight Trainer
		1	Integrated Gunnery Trainer
		1	Tactical Flight Trainer
		1	Weapon Systems Trainer
		3	Virtual Maintenance Trainer
Transport	CC130J Hercules	2	Full Mission Simulator
		3	Integrated Procedures Trainer
		1	Flight Training Device
		3	Fuselage Trainer
		1	Integrated Cockpit Trainer

[182] FlightGlobal and CAE, ‘Military Simulator Census 2020’.

The current use of virtual simulators in the RCAF spans nearly every fleet using devices that include a spectrum of fidelity. The simulators are used in training all aircrew and most ground crew positions on all modern fleets. This reinforces the strong buy-in of simulation and indicates a large inventory of models to support a constructive simulation capability.

Constructive Simulation

The use of constructive simulation in the RCAF is currently limited to niche capabilities within other organizations.

The development and retention of experienced pilots have become such a challenge that the RCAF had Defence Research and Development Canada (DRDC) develop the Pilot Production, Absorption, Retention Simulation (PARSim) to identify the importance of factors that affect pilot experience levels.[183]

The fluid dynamics effects of wind on RCN ships and how they affect RCAF helicopters is a cooperative study between DRDC's Atlantic Research Centre[184] and the National Research Council.[185] That study will develop models for constructive simulations to better define the dangerous ship-helicopter operating limitations.

Defence Research and Development Canada operates a Virtual Proving Ground (VPG) where electronic warfare (EW) threats are modelled in a constructive simulation,[186] allowing configurations of the aircraft defensive EW equipment to be proven effective.

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[183] René Séguin, 'PARSim, a Simulation Model of the Royal Canadian Air Force (RCAF) Pilot Occupation' (Ottawa, Canada: Defence R&D Canada, n.d.).

[184] Thornhill, 'Guidelines for Performing Ship Airwake Simulations on a Generic Destroyer'.

[185] Yuan, Lee, and Wall, 'Simulation of Unsteady Ship Airwakes Using Openfoam'.

[186] Rob Zellerer, 'Effectiveness of RCAF Countermeasures against Threats to Military', The Leading Edge, no. 5 (October 2012).

The Royal Canadian Navy has developed a powerful constructive simulation capability called the Maritime Modelling & Simulation Cell (MMSC). The MMSC has a computing cluster consisting of "88 servers accounting for ~3500 nodes which will support 3-4000 instances of simulation environments/scenarios running simultaneously as part of a Monte Carlo [simulation]."[187] This system has been used to optimize tactics used by aircraft and helicopters that are tracking submarines, threat response studies in support of RCN capability requirement analysis and has studied marine mammal interactions to support the use of sonar equipment.[188]

Research on pilot behaviour is conducted in a partnership between the RCAF and Carleton University's Advanced Cognitive Engineering Laboratory where five research simulators can be used to understand human factors and to advance pilot modelling.[189]

The MMSC capabilities may be available for RCAF projects, but the required human models represent an important difference between this work and the proposed use of constructive simulation in the RCAF. Decision-making models would be very similar, but human interaction models would be substantially different. On an RCN ship, the method that the helm is moved has little to do with the ship's performance,[190] whereas the method that helicopter controls are operated can vastly change the response of the helicopter.[191]

[187] Christopher Lien, 'CMWC Official Email', email to author, 13 April 2021.
[188] Ibid.
[189] Carleton Aerospace, 'Advanced Cognitive Engineering Laboratory', Carleton University, 2021, https://carleton.ca/aerospace/our-facilities/ace-simulator-labs-vsim-herdman-and-gamble/.
[190] Emil Schreiner, 'Naval Terminology', email to author, 11 April 2021.
[191] Author is an experimental test pilot and has evaluated control responses of numerous helicopter types including all RCAF types.

These examples demonstrate recognition of the value of constructive simulations and potential support for a constructive simulation capability, but there are also some issues worth considering. None of these is a robust capability that could quickly develop a solution to a new aerospace problem, so cannot be assumed available for a quick solution. Furthermore, R&D projects commit to studying a problem more so than delivering a capability. The similar research completed in different areas is inefficient: the value of innovation hubs has been measured[192] and is an SSE initiative.[193] The DND simulation support that is available to the RCAF demonstrates value in constructive simulation, some existing capabilities, but do not form an existing capability to the scope being discussed.

Modelling and Simulation (M&S) Training

The RCAF recognized the need for training its personnel in M&S so had established a sponsored post-graduate position to learn M&S at a Canadian University. There have only been a handful of graduates from that program but that is expected to increase as more Canadian Universities have recently made new M&S programs available.[194] The RCAF's Barker College delivers a one-week course, *Basic M&S*, that provides a broad, basic understanding of M&S. As it is a new course, there have only been 75 students complete it, but the demand for future delivery of the course is high.

The strong buy-in to simulation that the RCAF has demonstrated institutionally and individually has not yet generated a large number of simulation-trained personnel.

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[192] Richard Cardwell, 'Dedicated Innovation Hubs for a Successful Approach to Modernization', Infosys, 2021, https://www.infosys.com/insights/digital-future/dedicated-innovation-hubs.html.

[193] Canada. Department of National Defence, Strong, Secure, Engaged - Canada's Defence Policy., 77.

[194] Institute of Cognitive Science, 'Modelling and Simulation', Carleton University, 2021, https://carleton.ca/cognitivescience/research/clusters/modelling-and-simulation/.

The early growth of the training is positive, but this level of education is a weakness that must be considered when developing a constructive simulation capability.

CONCLUSION

The RCAF has built a very capable simulator capability, but with a strong focus on training. There is doctrine and education that will broaden the capability for the future, but constructive simulation capabilities remain as niche capabilities used for a specific purpose. The strong buy-in of simulation within the RCAF is further supported by the extensive uses of simulation.

CHAPTER 6. THE CHALLENGE

Although the benefits of a constructive simulation may be known to personnel within capability development of the RCAF, it is rarely employed. When the benefits of constructive simulation are considered along with the strong buy-in of simulation within the RCAF as well as the extensive existing use of virtual simulation in the RCAF, it may seem illogical that the constructive simulation capability has not been further developed. This is explained, at least in part, by some unique challenges to developing and employing a constructive simulation capability.

One challenge with this capability is that with it operating at the forefront of emerging technology it must continually develop. A home PC that is five years old may be unable to run new software.[195] Similarly, a constructive simulation capability that is not continually developing to embrace new technology risks obsolescence.

Consideration of the lifecycles of constructive and virtual simulations will reveal some important differences between the two. Notably, the virtual simulation is built once and used many times whereas the constructive simulation is a custom development for each use. The lifecycle identifies four elements of a constructive simulation. Their interactions will be analyzed to understand the challenges in developing this capability.

SIMULATION LIFECYCLE

The simulation lifecycle shows the flow between important steps in the definition, development, and execution of a simulation. The constructive simulation lifestyle is different from that of a live or a virtual simulation in that with the latter two the

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[195] Mike McEvoy, 'Why a Five Year Old Computer Is Slower Than a New Computer', HTS Tech Tips, 2021, https://www.htstechtips.com/2009/09/30/why-a-five-year-old-computer-is-slower-than-a-new-computer/.

simulation is defined and developed once and then is executed many times whereas the constructive simulation will be defined and developed for every new execution.

Consider a new idea for tactics in air-to-air combat manoeuvring. A constructive simulation could be used to exercise many different tactics to determine an optimal tactic.[196] The simulation would be developed for this problem and would be executed once. An existing virtual training simulator of a fighter aircraft, or the actual aircraft in a live simulation, could then be used to allow the pilots to rehearse the optimal tactic many times.[197] Neither the virtual nor the live simulation would require changes to support the new tactics.

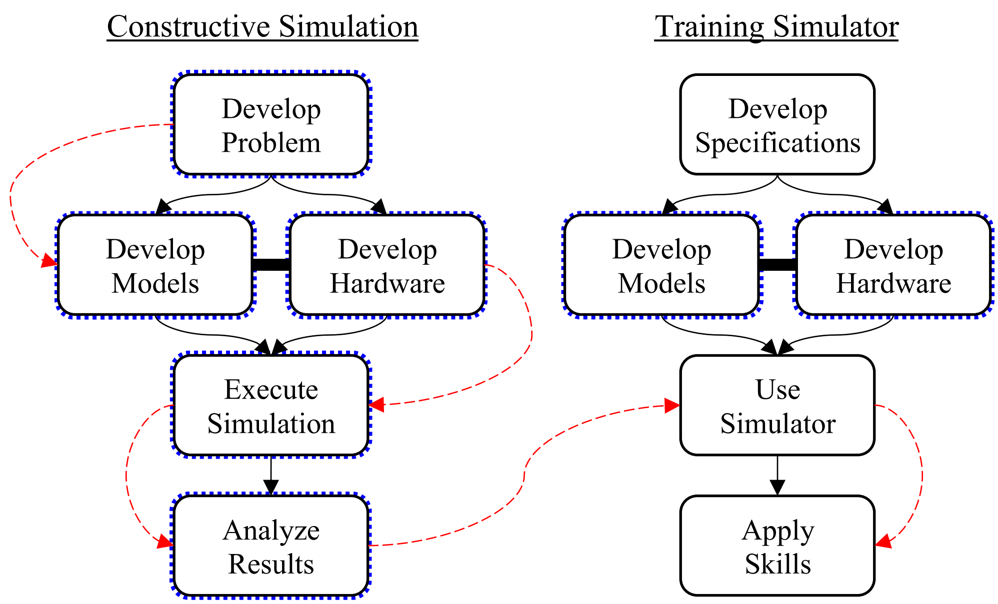

Figure 6.1 – Simulation Lifecycle Comparison[198]

Although different, the lifecycles of constructive and virtual simulations have many similarities, as illustrated in Figure 6.1. They start with a definition, either a problem for a constructive simulation or a training requirement that defines a

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[196] Burgin and Sidor, 'Rule-Based Air Combat Simulation'.
[197] Phillips, 'Journey Into Space Research', 63.
[198] Author's representation of the conceptual processes.

specification for a virtual simulation. Each then needs hardware and models to be developed and implemented. Executing the constructive simulation is analogous to using the training simulator to train. Finally, the analysis of the results is the output of the constructive simulation and the application of the newly refined skills is the output of the virtual simulation. The development of a new capability that uses both a constructive simulation to optimize a solution and a training simulator for pilots to develop the skills is shown by the flow of the dashed red lines. Each step of the process requires effort by different personnel, but the steps indicated with a blue-dotted outline require the effort of simulator specialists: personnel with science, engineering, or operational experience and with a deep understanding of simulation.

THE FOUR ELEMENTS

The simulation lifecycles in Figure 6.1 also suggest the elements of each simulation domain: the problems to solve or specification for a virtual simulator, the models, the hardware, and the personnel. The similarity between the lifecycles accurately suggests there is opportunity to transport elements from one simulation into another. Consideration of each of the four elements will show challenges within the elements and with using existing sources.

Problems to Solve

The constructive simulation lifecycle starts with the problem for the capability to solve. The problem then guides the development of the hardware and models, and thus guides the development of the capability. A suitable problem is also developing the capability where it is needed.

It can be challenging to identify suitable problems for three reasons. First, not every problem is suitable for constructive simulation. Problems that can be solved analytically or problems that rely on qualitative data may best be solved with other means. Second, the problem must be at a suitable difficulty. If the capability so far had only solved relatively simple problems, then difficult ones could force an enormous effort to transform the capability. Moderate increases in complexity are manageable because the models and the hardware are custom designed for each execution so some effort to transform will occur regardless. Finally, the problems must be relevant to the RCAF. This requires simulator personnel to be aware of RCAF activities and for RCAF personnel outside this capability to be aware of what it can do.

The requirement for problems to be relevant to the RCAF creates another challenge. Much of the RCAF operate under secret or top-secret security classifications. If any content must be at a higher classification, then everything must be treated like it is. Every person working on the problem, every computer used in the problem, every piece of paper produced, every model developed, and every building where work is completed must comply with demanding security restrictions. Unless the level of security can be assured, many problems that could be analyzed with a constructive simulation would have to be excluded.

With a problem defined, the development of the simulation would commence. Hardware and models are developed together, but the complexity of the models will affect the requirements of the hardware, so models are next considered.

Models

As discussed in Chapter 2, a training simulation would be developed with many different models, developed only to the fidelity required for the intended purpose. For example, a helicopter simulator designed to train basic flying skills but not mountain flying skills, would not require the additional fidelity needed for mountain flying. The weather model may not include complex wind patterns, the terrain model may not include mountainous regions, and the engine model and flight dynamics model may not match true performance at high altitudes. The importance of rigour in developing specifications is evident, as a model can be unsuitable for simulations of conditions not detailed in the specification.

The constructive simulation process has the development of models as a step in the lifecycle of every problem undertaken. This would require simulator specialists to select an existing model, modify an existing model, or develop a new model for each model required in the simulation. This may be a simple development of the 'bang-bang' controller used in residential heating systems,[199] essentially two lines of code, or it could be a flight model that requires costly, potentially dangerous, flight test and months of analysis to develop.[200] After the development of models is complete, they must be implemented into the simulation and then undergo verification and validation.[201]

The number of models available for re-use is a measure of the growth of this element. The first time a flight model for a particular aircraft is needed, the effort is

[199] Katsuhiko Ogata, Modern Control Engineering, 5th ed, Prentice-Hall Electrical Engineering Series. Instrumentation and Controls Series (Boston: Prentice-Hall, 2010), 22.

[200] Dreier, Introduction to Helicopter and Tiltrotor Simulation, 104.

[201] R. Srinivasan, D. Collins, and S. J. R. P. Carignan, 'NRC Bell 412HP Flight Test and Data Collection for CAE's Simulator Model Validation.', n.d.

tremendous. The next time it is needed, it may only require a few keystrokes to copy and paste the files. The re-use of models introduces the same rigour required during the development of specifications for a virtual simulator. If a model's fidelity is too low, it will not provide the required detail and will fail verification and validation. For efficiency in development, a model with higher fidelity than required may be selected, knowing it may cause actual time of execution to extend undesirably.

The Human Model

The feasibility of models of human pilots that may be needed to control a constructive simulation has prevented extensive development of aerospace constructive simulation until recently. New theories in logic, artificial intelligence, neural networks, and cognitive science have allowed the development of advanced human pilot models. These models may be logical models that only represent decisions,[202] an element of a feedback control system that imitates the neuro-muscular delay,[203] or they could be complex mathematical and logic algorithms that represent the human decision-making logic and the human inputs into controls.[204] The most complex of the three examples is typically required for the more dynamic aerospace applications like military helicopter operations and air combat manoeuvring where pilots are needed to monitor the safe operating envelope, make rapid decisions, and provide fast, accurate control inputs. From a 1988 air combat simulation study, the response times during "real-time close-in air-to-air combat simulations with a human pilot in the loop are between 10 and 50

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[202] Mohammadian, Sarker, and Yao, Computational Intelligence in Control.
[203] McRuer and Krendel, 'Mathematical Models of Human Pilot Behavior'.
[204] Lone and Cooke, 'Pilot-Model-in-the-Loop Simulation Environment to Study Large Aircraft Dynamics'.

milliseconds"[205] making an advanced human pilot model necessary. Alternately, a constructive simulation that optimizes the delivery schedule for transport aircraft may run effectively using only a decision-making model requiring response times no faster than the 8 seconds required from a "hands-off inattentive pilot."[206]

For this capability to develop into the desired robust constructive simulation capability, a robust human pilot model would be required. Currently, advanced pilot models are only available for limited mission profiles.[207] Modification or development of a robust human pilot model is a tremendous challenge that will require, as a minimum, a team of control engineers, software engineers, mathematicians, cognitive scientists, and pilots. The pilot is the simulant but is also an intelligent participant that would add real-world experiences into the model.[208] The cognitive scientists would strive to understand the pilot's decision-making processes and control methods and then detail them as thought algorithms.[209] Other specialists may use nonlinear control systems, fuzzy logic, neural networks, or new technologies to implement the thought algorithms.[210] The control engineers and software engineers would implement the mathematical models into the simulation.[211] The model would then undergo rigorous verification and validation to ensure it is simulating the pilot's actions as intended.[212] Like any advanced model, the

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[205] Burgin and Sidor, 'Rule-Based Air Combat Simulation', 1–5.
[206] The United Kingdom. Ministry of Defence, Certification Specification for Airworthiness.
[207] Lone and Cooke, 'Pilot-Model-in-the-Loop Simulation Environment to Study Large Aircraft Dynamics'.
[208] Gideon Singer, 'Methods for Validating Cockpit Design' (Stockholm, Sweden: Kungliga Tekniska Högskolan, March 2002).
[209] Klaproth, 'Tracing Pilots' Situation Assessment by Neuroadaptive Cognitive Modeling'.
[210] Richards and US Department of Defense; Defense Technical Information Center, 'Artificial Intelligence Techniques for Pilot Approach Decision Aid Logic (PADAL) System'.
[211] McRuer and Krendel, 'Mathematical Models of Human Pilot Behavior'.
[212] R G Sargent, 'Verification and Validation of Simulation Models', Journal of Simulation 7, no. 1 (February 2013): 12–24, doi:10.1057/jos.2012.20.

human pilot model requires a tremendous effort to develop the first time but may be a few keystrokes to cut and paste the files for its second use.

With models identified, their complexity is an important input into the hardware requirements as more complex models would require greater hardware performance.

Hardware

Hardware is a simulation element where training simulators and constructive simulation show little similarity. Unlike a constructive simulation, training simulators require inputs and outputs to guide the simulation. An aircraft simulator would have flight controls as inputs and motion and displays as outputs.

When considering only the computers that execute the models there are important differences between training simulators and constructive simulations. The training simulator is designed to generate data that creates the output effects based on the inputs. There is no requirement to retain the data so it is erased. The training simulator's computer hardware is designed to operate the simulation at real-time, and for efficiency is unlikely to operate much faster. A constructive simulation generates data for analysis after the simulation is complete. This demands a large storage capacity and high data transfer rates. Whether a slow-time CFD simulation of air around a wing or a fast-time Monte Carlo simulation of driving routes from work to home, a constructive simulation will run as quickly as resources permit.

<u>Computer Performance</u>

Hardware performance in a constructive simulation is a balance between the cost and the required processing speed, data transfer rate, and data storage capacity. A training simulator solves this balance by ensuring sufficient processing speed and data transfer rate to meet the real-time requirement; it will provide just enough performance. A constructive simulation solves this balance first by meeting minimum requirements, then by increasing performance to provide results when they are needed; it will provide just-in-time performance.

Because the hardware for training simulators is built once and used many times, just enough performance will suffice for the lifetime of the capability. For a constructive simulation, the hardware is selected based on the problem. A problem requiring high performance may suggest that a multi-million-dollar supercomputer[213] is required, but a problem requiring low performance could be run on a home PC. In many ways, this disparity between cost efficiency and minimum performance is mitigated by building computer clusters.

Computer Clusters

Twenty years ago, personal computers were providing low-cost, high-performance computing capabilities. With networking and software tools, engineers were able to connect several personal computers into a cluster where each computer can contribute to the execution of a complex calculation. These clusters were able to achieve the performance of the fastest supercomputers at a fraction of the cost.[214] Because the size of a cluster can be increased by removing or by adding individual computers, or *nodes*, the cluster is scalable to provide the performance required for a particular calculation. The data transfer rate of a cluster is strongly tied to the networking hardware used to link the nodes, but the processing speed and data storage capacity are both

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[213] Keith Wagstaff, 'What, Exactly, Is a Supercomputer?', Time, 19 June 2012, https://techland.time.com/2012/06/19/what-exactly-is-a-supercomputer/.

[214] David A. Bader and Robert Pennington, 'Applications', The International Journal of High Performance Computing Applications 15, no. 2 (1 May 2001): 181–85, doi:10.1177/109434200101500211.

modular. This scalability allows optimization of computer performance and resource efficiency for a particular constructive simulation execution, by including only as many nodes and as much data storage as needed for the problem and freeing the remaining hardware for other problems.

Figure 6.2 – The Jupiter CFD Cluster at the University of Liverpool[215]

Figure 6.2 shows the University of Liverpool's Jupiter CFD Cluster, a computer cluster used for CFD simulations that was built with 192 nodes, each a home PC using 20-year-old Pentium IV processors, and networked with standard ethernet hardware.[216]

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[215] School of Engineering, 'The Jupiter CFD Cluster', University of Liverpool, 2021, https://www.liverpool.ac.uk/flight-science/facilities/jupiter4/.

[216] Ibid.

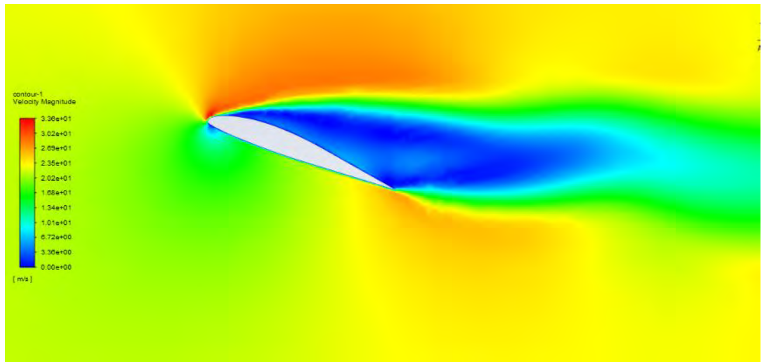

Figure 6.3 – Airflow speeds of a Stalled CH146 Griffon Main Rotor Blade[217]

The full benefit of the computer cluster can be seen in the reduction of actual time due to the increased computer performance. Consider the development of a CFD animation of airflow around the main rotor blade of the CH146 Griffon helicopter. Figure 6.3 is a frame in an animation that covers 14 seconds of simulated time. Using a powerful home computer, the actual time of the execution was 29 hours. If this were executed on the Jupiter cluster, for example, the actual time would have been approximately 3 minutes.

Hardware Available to RCAF

Many simulations can be executed on a standard PC, of which there are thousands within the RCAF. More capable computers and computer clusters are available within the department and within the GoC. For example, Shared Services Canada provides a High-Performance Computing capability to all GoC departments that include "the fastest recorded computer platform in the Government of Canada and among the fastest in the world."[218] Furthermore, there are commercially available computer clusters in Canada,

[217] Developed by the author using Ansys Fluent software package, 2020.
[218] Shared Services Canada, 'High Performance Computing'.

including 10 of the world's 500 fastest computer systems,[219] as well as capabilities within the DND but external to the RCAF.

The availability of suitably performing hardware potentially allows the RCAF to execute constructive simulations by outsourcing the hardware capability. However, high-performance clusters are expensive and thus are unlikely to have high availability, especially for a time-sensitive problem. Also, since many of RCAFs capabilities require higher security classifications, the existing systems may not be suitable.

The hardware element is more than the computers. It is also the expertise required to implement a system that performs as required for each unique simulation. The hardware specialists work with the other simulation specialists to develop the correct simulation for each problem. The personnel are the fourth element of the constructive simulation and have a vastly different role than counterparts for a training simulator.

Personnel

The training simulator is assembled by a team of simulator specialists, by following a detailed specification of the training that will be conducted and the equipment that will be simulated. Once developed, the simulator specialists likely will not work on the training simulator again throughout its product life. Figure 6.1 shows the specialists are only used during model and hardware development on training simulators. The maintenance and support of the training simulator are conducted by technicians with specialist knowledge of the computers and the mechanical systems and are not the specialists who develop models and design hardware.

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[219] Strohmaier et al., 'TOP500 List - November 2020'.

A constructive simulation uses simulation specialists at every step of its lifecycle. Figure 6.1 shows that the specialist skills are used throughout a constructive simulation's life. Developing the problem may require operators, physicists, engineers, human factors scientists, and many other disciplines. A similar team would develop and integrate the needed models. Data scientists and computer engineers would collaborate on optimizing the hardware. Ideally, each of the specialists would understand the problem from many perspectives as the solution is an integration of all those fields.

For the RCAF to develop a constructive simulation capability, these specialists must be available. It is highly desirable that the specialists share an aerospace and RCAF operations perspective, as that perspective must be applied when developing the problem and analyzing the results. Although training in simulation has begun and experienced personnel can be found in the RCAF, there are still very few people with formal RCAF training in simulation.

Teams of qualified personnel could be developed by reaching outside the RCAF and perhaps outside DND, but then challenges with employing this broad base of expertise would arise. That would include a lack of unity in that they all work in different organizations, a lack of standard practices in that each organization may use unique methods, and a lack of availability. Those three challenges mean that every problem would need to start with developing a new team rather than starting with a cohesive group.

Training simulators also operate with people, but they support the operation of a device that may continue to operate for days without any involvement. Constructive simulation is vastly different. The personnel, like the other three elements, are essential to each use of the capability. Also, each element grows through their interactions with the other elements.

GROWTH OF THE ELEMENTS

The interaction of the four elements is important because this constructive simulation capability is neither an off-the-shelf purchase nor a one-time build. It is a capability that requires a custom build of a simulation every time the process is used, and with every build, more capability can be produced. The natural lifecycle of the capability causes growth provided suitable problems are presented.

For the RCAF to maintain constructive simulation as a capability, the problems must support RCAF efforts. Each problem must have simulator specialists developing new models, new hardware, and new analyses thus each problem develops the capability. When the team of specialists works on a new problem, the specialists are also developing. To grow the capability or to avoid obsolescence it is important that problems are identified that are suitable to support both the RCAF and the constructive simulation capability. It cannot be guaranteed that each problem supports the RCAF and grows each element equally. This would require a diverse set of problems that the capability sequences, within RCAF priorities, to guide the development of the elements.

By selecting problems from a diverse set, the capability can provide solutions for problems while it grows capabilities to support more difficult problems. There may be the opportunity to advance low priority problems to challenge personnel that may be under-utilized.

A challenge in identifying a diverse set of problems comes from the realization that the problems come from RCAF personnel who are unlikely to be simulation specialists. For those people to understand which problems may be solved with constructive simulation, they must be up to date with the potential of the constructive simulation capability. The potential of the capability is seen in the success of previous problems. If the capability were to grow suddenly, then it is unlikely that suitable problems will be identified. With steady growth and a steady capability increase seen in the results, awareness should be created that supports the delivery of suitable problems.

The growth would continue towards a robust capability when the capability of each element is supporting the available and forecast problems. This observation leads to the definition of a robust constructive simulation capability for the RCAF: A team of RCAF and specialist personnel working in a top-secret facility with dedicated high-performance computer systems and a library of models of varying fidelity that includes aircraft, weapons, equipment, and human pilot models.

Achieving a robust capability does not imply growth stops as new technologies will be incorporated when needed. This capability would grow throughout its life.

CONCLUSION

This chapter focused on elements of a constructive simulation: the problem, the models, the hardware, and the personnel. It compared existing RCAF capabilities with each element and found limited support due to challenges unique to this capability.

The capability requires a diverse set of problems that support both the RCAF and the growth of the capability. This would come from personnel throughout the RCAF who understand the capability and can identify suitable problems. Generating the diverse set of problems thus requires educating more RCAF personnel in simulation and ensuring the results and capabilities of constructive simulation are shared across the RCAF.

An organic constructive simulation capability would require developing and integrating complicated models, developing a powerful and secure computer capability, and employing a team of highly trained personnel. These elements will grow when challenged with new problems that require additional development of the capability.

This chapter developed an understanding of this capability by studying its constituent elements. The earlier demonstration of a problem with airpower complexity, the viability of constructive simulation to address such problems, and the buy-in of simulation within the RCAF, suggest this capability will be supported by the RCAF. The remaining challenge is to identify GoC support and a means to procure the capability within the government's procurement regulations.

CHAPTER 7. PROCUREMENT TIMELINE TO A USEFUL CAPABILITY

The RCAF is experiencing significant challenges in developing new capabilities that include the latest technologies and is experiencing delays on many of its critical procurements. The new technologies offer a viable avenue to counter many of the issues the RCAF is facing by developing a constructive simulation capability. While there is an extensive inventory of simulation models and hardware and there are many RCAF personnel working in simulation, each of these areas is not sufficient to support a robust constructive simulation capability and must be developed through procurement, training, and generating experience.

The actual timeline to procure this capability is dependant on the support the capability receives. It could start small and grow slowly or start with a strong investment and grow rapidly. Too rapid growth becomes a challenge as personnel must be trained and must gain experience with the development of models and hardware. Based on the growth of the RCN's MMSC, the development of an initial capability with dedicated personnel and infrastructure would take at least four years and a robust capability would take more than eight years.[220] The time to start the procurement of this capability is now, as the issues with the complexity of airpower are already occurring. However, this research is focused on the maturity of the technology and whether it has advanced to a point where it can support the RCAF and does not consider the relative priority of the many other projects. That analysis must occur before the best timeline can be determined.

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[220] Jamie Parsons, CF Maritime Warfare Centre, telephone conversation with author, 2 April 2021

Perhaps the greatest challenge in building this capability will be meeting the requirements of the procurement process. First, the CAF must demonstrate "a deficiency or an emerging requirement in current…capabilities."[221] Next, a business case analysis must compare viable options and confirm that the "intended benefits are…relevant and attainable."[222] If expenditure authority is obtained, then there would be a competition to find an eligible company to provide the goods and services. Finally, the capability is "tested and verified by DND and CAF"[223] before delivery of the full capability. While few projects encounter challenges to progression, the development of a robust constructive simulation capability is likely to encounter significant challenges at each of these steps and potentially many others. By understanding how this capability conflicts with the procurement process, a modified approach to procurement is proposed.

PROCUREMENT CHALLENGES

A constructive simulation capability could become the RCAF's most technologically advanced capability, oxymoronically designed to counter issues experienced when developing technologically advanced capabilities. The nature of the capability is that it is a tool that can be used in many areas and that it must grow after procurement. It is not intended to directly solve problems with airpower complexity but is to provide support towards those problems. Those characteristics create procurement challenges in defining a capability deficiency, identifying attainable benefits, creating a project suitable for outsourcing, and determining how to conduct test and evaluation.

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[221] Canada. Department of National Defence, 'Defence Purchases and Upgrades Process'.
[222] Canada. Treasury Board, 'Directive on the Management of Projects and Programmes'.
[223] Canada. Department of National Defence, 'Defence Purchases and Upgrades Process'.

A Capability Deficiency

The underlying problem that identifies constructive simulation as a solution for the RCAF is the increasing complexity of developing, training, and employing airpower capabilities. The complexity arises from the necessary inclusion of rapidly advancing technology. The challenge in procuring a constructive simulation capability to address this deficiency lies in the distance between discussing the problem and demonstrating it as a viable solution. It is not a direct fix to a single problem, rather is a tool that when used effectively will support a variety of problems.

Relevant and Attainable Benefits

Chapter 6 discussed the development of a constructive simulation capability and how each of the four elements (model, hardware, personnel, and problems) support the development of the others. It is unlikely that a robust constructive simulation capability can be procured as an off-the-shelf solution, especially when considering that many of the models must be of RCAF equipment, not generic aircraft, and that the personnel must understand RCAF procedures. This suggests that the capability that can be procured will initially be unable to provide solutions to all the problems discussed in Chapter 1. Instead, the procured capability will require development.

The time to grow the capability would be inversely proportional to the investment in the capability, in that a large facility, with powerful computers, and many highly experienced specialists should be able to achieve incremental successes in a short time that would develop the capability quickly. Unfortunately, the expected benefits from such a project would be proportional to the investment so a high-cost procurement would have had to promise greater successes. Alternately, a low-cost procurement could promise and achieve less ambitious results, but those may not address the capability deficiency.

Eligible Companies - Outsourcing

A viable method of procuring this capability could be a contractor-operated solution where many of the specialist personnel and the operation of the computer systems may be outsourced to a company. There is a known risk to outsourcing within the Information Technology domain where the "lack of business or domain knowledge"[224] provides ineffective results especially where outsourcing demands "advanced research and analytical, technical, and decision-making skills."[225] The contractor would need to have an understanding of RCAF processes to develop constructive simulations in support of RCAF problems.

As previously discussed, there is little chance that a company exists that can offer an off-the-shelf robust capability, so a contracted solution would also need development through interaction between the four elements. In this case, there is a potential barrier between the capability provided by the contractor and the problems provided by the RCAF. If the RCAF personnel, who are the identifiers of new problems, are not integrated into the capability, then it will be challenging for them to identify developmental problems that support expanding the capability.

There have been successful partnerships in similar contract relationships, but there have also been some notable disastrous partnerships. The 2006 loss of a Royal Air Force Nimrod aircraft and crew was attributed to a contracted airworthiness process that

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[224] Overby, 'What Is Outsourcing? Definitions, Best Practices, Challenges and Advice'.
[225] Ibid.

was followed on paper but was not considered as a measure to protect RAF personnel. The lead investigator, Sir Charles Haddon-Cave, warned that “it is important not to outsource your thinking and to remain an ‘intelligent customer’.”[226] A risk with an outsourced capability can occur if too much confidence is bestowed on the contractor. The RCAF could lose insight into the development of the capability and could lose the ability to present suitable problems. Remaining integrated with the outsourced capability could keep the RCAF an intelligent customer.

Test and Verification

The implementation phase process of testing and verifying the equipment or services provided by a contractor before the RCAF accepting them presents an important challenge when procuring a constructive simulation capability.[227] Because a robust off-the-shelf capability is not available, a capability that will develop over time must be procured but that capability must be accepted on delivery before the development occurs. It is possible to accept a primitive prototype, provided the contract specifies it. The problem is that a primitive prototype would be unable to provide the benefits needed or satisfy the capability deficiency.

A CASE FOR GROWTH

The four procurement challenges discussed above suggest that it is not possible to procure a capability that needs to develop after procurement before it can provide the intended benefits. This is true for projects procured under Canada’s Defence Production

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[226] Haddon-Cave, ‘Leadership & Culture, Principles & Professionalism, Simplicity & Safety - Lessons from the Nimrod Review’, 6.

[227] Canada. Department of Justice, Financial Administration Act, pt. 34.

Act[228] but there are other methods where government funds support the development of a capability, such as the use of Innovation funds.[229] Innovation funding is not suitable for a capability as it only funds the initial creation of a concept and not the sustainment costs for the projected life of the capability. A classified computer facility with simulation specialists may cost tens or hundreds of millions of dollars to procure and then millions of dollars per year in operating expenses.[230] Creating the capability within an R&D project would still require executing the project approval process to receive expenditure authority to support the infrastructure and sustainment costs.

The solution to the procurement challenges is to understand the requirement for the capability to grow, understand the procurement policies, and identify a procurement model that allows the development to occur.

Growth Capability

An apparent solution to this dilemma is to procure a capability with the expectation that it will grow to meet the required benefits. There are methods within the defence procurement processes to define incremental requirements that allow acceptance of the product, with a requirement for the capability to meet greater requirements as it develops.[231] This is also incompatible with developing technologies because even though the future capabilities may be imagined, it would not be possible to determine when in the future they will become available.

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[228] Canada. Minister of Justice, Defence Production Act.
[229] Government of Canada, 'Innovation Funding and Support', Government of Canada, 8 January 2021, https://www.canada.ca/en/services/science/innovation/funding.html.
[230] Wagstaff, 'What, Exactly, Is a Supercomputer?'
[231] Canada. Department of National Defence, Project Approval Directive (PAD), 41.

Many projects do anticipate the development of capabilities during implementation. This has been a method within the RCAF to manage emerging technologies during the acquisition of complex capabilities. The procurement of the CH148 Cyclone helicopter was one such program that was deemed an off-the-shelf purchase but with developmental elements. The Fall 2010 Auditor General of Canada report identified numerous issues with the developmental nature of the procurement. Updated requirements to allow growth potential were inconsistent with the competitive bid and, assuming the original requirements were sufficient, the government was paying for more capability than the RCAF required.[232] This is a result of having specifications for the project that were developed before 1999 and the delivery of the helicopters beginning in 2013.[233] The Auditor-General report questioned "whether a lowest price compliant strategy is compatible with the acquisition of complex military equipment requiring significant development."[234]

Spiral Development

In addition to the above problems with the procurement process, the implementation phase of a developmental project without detailed, fixed specifications will often encounter an effort- and time-wasting phenomenon called *spiral development* after Barry Boehm's concept to improve software development[235] where development is based on early specifications and technological or commercial successes are used to enhance the next level of specifications. Development occurs in a cycle of specifications,

[232] Canada and Office of the Auditor General, 'Acquisition of Military Helicopters.', 6–13.
[233] Ibid., 6–2.
[234] Ibid., 6–13.
[235] Boehm, 'A Spiral Model of Software Development and Enhancement'.

delivery, analysis and then a redefining of specifications.[236] At each cycle the product grows towards an undefined but desirable end state, hence a spiral growth. The many versions and releases of complex software systems, such as Microsoft Flight Simulator, are a result of the economic successes of Boehm's model. A military procurement does not get the opportunity to generate revenue within each cycle and the result is a *specify – prototype – test* cycle that may continue to grow but never end at the desired specification. A 2008 analysis recommended the use of spiral development for defence procurement in the United States provided it is "based on proven mature technology"[237] as it identified "risky development strategies"[238] where "immature technology could not meet design specifications"[239] and resulted in cost escalation.

Spiral development is also problematic within the defence procurement process as each spiral cycle represents a change in specification with the possibility of procuring beyond the initial requirement.

POSSIBLE SOLUTIONS

The procurement of a constructive simulation capability must consider the essential nature of its growth through the interaction of the four elements of the simulation: models, hardware, personnel, and problems. The procurement must also align with the defence procurement process where the deficiency is addressed with a proposal that will achieve relevant and attainable benefits within the project timeline. A

[236] Ibid.
[237] Gansler, Lucyshyn, and Spiers, 'Using Spiral Development to Reduce Acquisition Cycle Times', 54.
[238] Ibid., 8.
[239] Ibid.

developmental process is necessary, as is a lowest price compliant competitive bid, a combination for which the Auditor General for Canada questioned the compatibility.

Project Models

One potential solution is to separate the continuous growth of the capability into multiple projects of advancing complexity[240] (see Figure 7.1). An initial capability is proposed that will allow the development of models and will grow experience but will not produce many results directly in support of the RCAF. The experiences from that small project could then be used to define a larger capability that will further grow and will produce more results for the RCAF, but still not to the extent that the aerospace complexities are addressed as intended. Since each project may take years from specification to producing results, even with projects overlapping, the timeline to a robust capability could be undesirable.

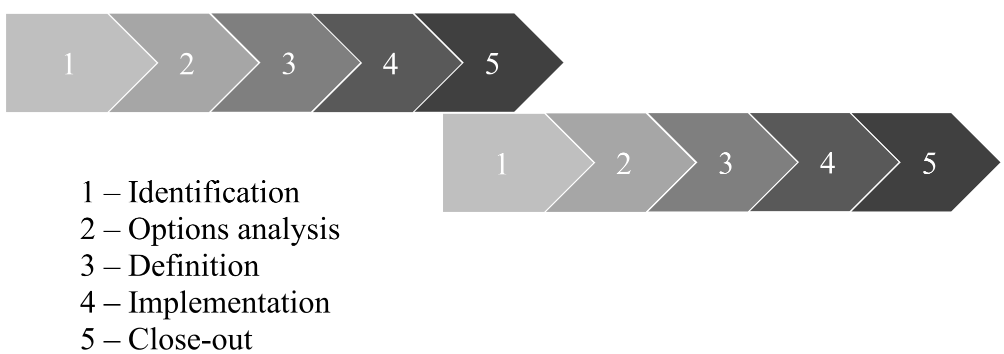

Figure 7.1 – The Multi-project Programme[241]

[240] Canada. Department of National Defence, Project Approval Directive (PAD), 44.

[241] Author's representation of material from Canada. Department of National Defence, Project Approval Directive, 2019

Similar to a program of multiple projects is the Cyclical Project[242] (Figure 7.2), where each cycle builds on the previous cycle and "aims to deliver a useful capability."[243] A cyclical project is well suited for projects that need to "reduce complexity and risk when dealing with unstable or emerging technologies."[244] The requirements are continually refined at each stage to define the exact end state, creating a requirement for additional project management effort and additional oversight. The cyclical project is intended to develop a capability incrementally, requiring the challenging foresight of identifying where the technology will progress within the time frame of each cycle.

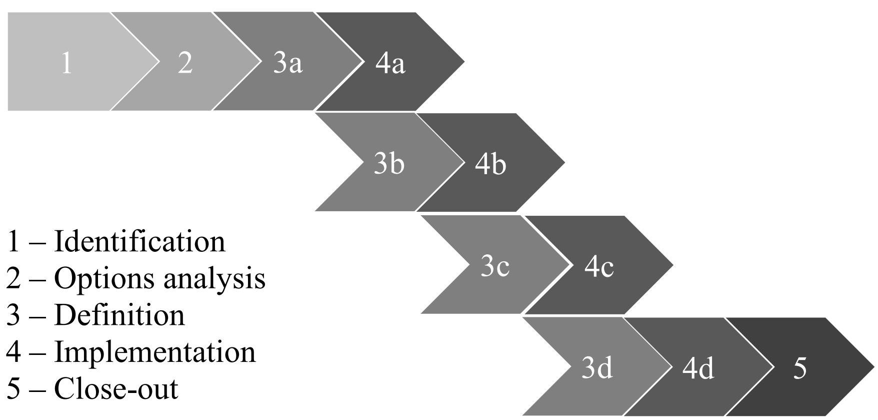

Figure 7.2 – The Cyclical Project[245]

The cyclical project model offers advantages over the multi-project model, as it uses one identification, one options analysis phase and one close-out phase. It allows a definition phase to be concurrent to the previous cycle's implementation phase. A multi-project model could allow an identification phase to run concurrent to the previous close-out, but it would be unproductive to run it earlier as the detailed requirements identified

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[242] Canada. Department of National Defence, Project Approval Directive (PAD).
[243] Ibid., 42.
[244] Ibid.
[245] Author's representation of material from Canada. Department of National Defence, Project Approval Directive, 2019

during identification phase would have to follow the results of the previous implementation.

An important challenge with the cyclical model and the understanding of the interaction of the four elements is the inability to predict the relative progression of each element. A cyclical model may predict a requirement for increased computing power at each step, but then the presented problems may not require upgrading the hardware. The expenditure authority does not allow a project to shift funds between all elements of the project, demanding reasonable estimates of the progression of each element. The growth of the capability is dependent on the existing capability, the emerging technologies, and the problems presented so a reasonable estimate of the progression of each would be required for the cyclical model.

Key Observations

The key to a viable solution comes from the interaction of the four elements and the understanding of the available project models. The solution flows from the following four observations.

First, the project approval must allow refinement of specifications throughout the development of the capability. This is a direct result of the requirement to procure to a specification, with specifications based on emerging and unpredictable technological breakthroughs.

Second, spiral development is necessary. The inability to specify attainable requirements until the capability further develops implies a spiral development construct. This cannot become the problematic cycle that does not converge to a final specification, so must be done with managed steps and oversight. Both cyclical projects and multi-project programmes would provide this.

Third, project timelines must be reduced to allow the incorporation of new technologies. Specifications from technology written only five years earlier would deliver underwhelming performance and poor value. The advancement of such technology and the incorporation into consumer products is measured in months vice years.

Four, the development of each of the four elements is unique and is a result of the problems presented, and the problems presented depend on the previous results. This was the conclusion of Chapter 6 and is a critical concept to understand when developing this capability. The project process can not guide the development of each element, instead, the process must allow each element to develop independently.

Spiral Growth

A potential solution to the many contradictions in this procurement that considers the four observations above, is to redefine the spiral development process to align with the expected growth in each area. The four elements could be captured in three connected projects: a cyclical project that procures computer systems, a second cyclical project that expands the size of the organization (i.e., the infrastructure and numbers of personnel), and a sustainment project that supports operations of the organization. The sustainment project could be cyclical, as the expenses would depend on the progress of the other two systems. Sustainment would also have to support additional training to ensure the RCAF personnel advance with the capability and pose problems at a suitable level to support further growth.

The three cyclical projects would be coordinated under a multi-project programme. It would offer responsive specifications to emerging technologies, it would ensure relevant project management for the whole capability, would ensure the oversight is provided throughout, and most importantly it would allow growth where and when the capability is ready for growth. With a focus on the growth of different elements of the capability, this construct is better explained as *spiral growth* of the capability.

Figure 7.3 is the author's depiction of this Spiral Growth project model. Each cyclical project is represented in a different colour, using the scheme depicted in Figure 7.2. The capability of each cyclical project grows outward but is spirally connected with the other two projects. Note that the identification and options analysis phases for the three cyclical projects are concurrent and could each be executed as a single identification and a single options analysis phase. The same may be true for close-out, but one of the strengths of this proposal is the ability to allow each cyclical model to progress at its own rate.

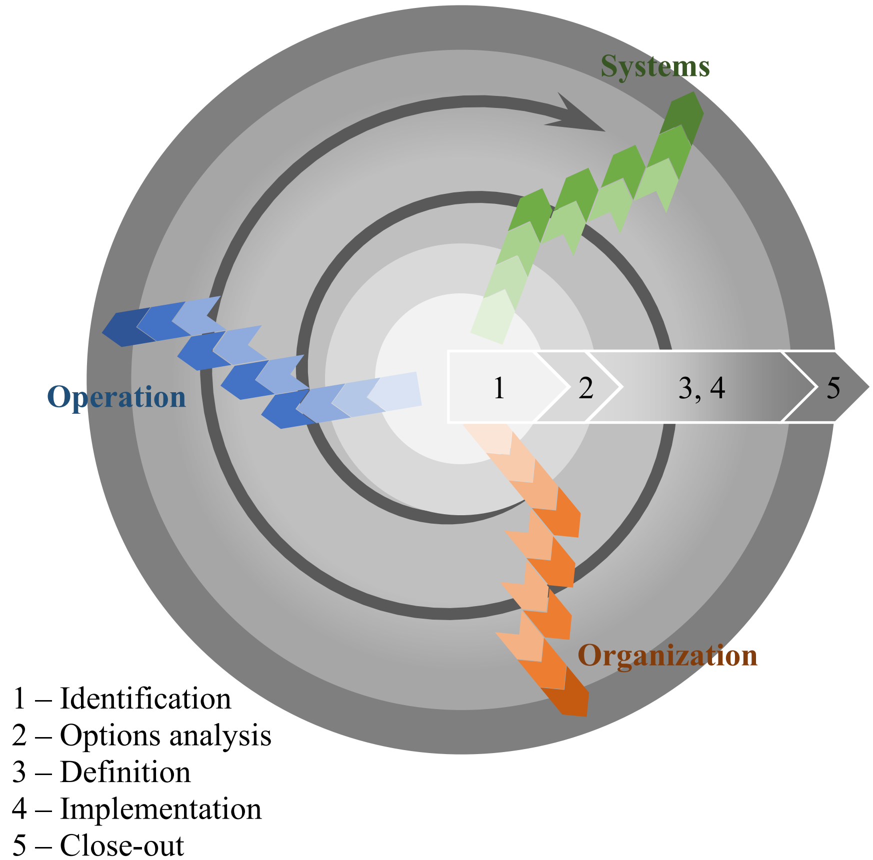

Figure 7.3 -The Spiral Growth Project Model[246]

Three project models were identified that could support procurement of the constructive simulation capability for the RCAF: the cyclical model, the multi-project programme, and the spiral growth model. Each model would be able to respond to the challenges of this procurement, notably the requirement for the capability to grow. The multi-project program requires less commitment to the long-term capability but would also be the longest duration project. The cyclical model would be more rapid but may be less able to support growth where it is needed. The spiral growth model allows growth

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[246] Author's depiction of the hybrid model.

where needed but as an unconventional model may be more challenging to achieve support and would involve greater oversight.

RECOMMENDATIONS

The need for a means to deal with the complexities of procuring, training, and employing airpower is clear. The use of constructive simulation to reduce that complexity is promising. It is viable in that the technology has advanced to make it possible to develop models of sufficient fidelity, plus the accelerating use of simulation within normal RCAF functions has increased buy-in of simulation to the extent that such new uses are quickly adopted. A real challenge with constructive simulation is that it is something that can be developed, but it is not assured to provide a solution to the most complex problems. That creates challenges in project approval as the intended benefits must be viable and attainable.

The spiral growth project model allows the development of a limited constructive simulation capability and then permits its growth. The spiral growth model allows each element of the simulation to grow when needed and when it is ready. Finally, because the spiral growth model advances with incremental approvals within each cyclical project model, there are opportunities to cease or delay development if further growth is unnecessary or not viable.

The three project models presented are viable means to procure this capability. The additional effort in achieving support to the spiral growth model would require greater project management effort at the start of the project, but the natural growth that the model permits would reduce project management effort over the life of the project. The additional oversight that may be provided with the spiral growth model may create additional project management effort but would not adversely affect the capability. The use of the spiral growth project model is recommended to procure a constructive simulation capability that will allow the RCAF to support the problems that come from the complexities of airpower.

CONCLUSION

Government procurement in Canada is a massive challenge that manages hundreds of manufacturers, on thousands of projects and spending billions of dollars.[247] Guidelines for project models are necessary to maintain order in that complexity. The guidelines do not account for every situation and smart procurement must consider unique circumstances. By examining the procurement processes and comparing with characteristics of the constructive simulation capability, three viable project models were identified. Two that were standard models create challenges in permitting the natural growth of the capability. The third is the spiral growth model, a hybrid model that is not specified in project management sources but is well aligned with the procurement acts and guidelines. The spiral growth model's ability to allow natural growth of the capability outweigh the additional project management effort that that model may require. The spiral growth model is recommended as a means to procure a constructive simulation capability for the RCAF.

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[247] Canada. Public Services and Procurement, 'Buying and Selling - PSPC', Government of Canada, 18 February 2021, https://www.tpsgc-pwgsc.gc.ca/app-acq/index-eng.html.

CHAPTER 8. CONCLUSION

Airpower is complex. This complexity has created problems with procuring, training, and employing modern airpower capabilities. Contributing to the complexity is the increasing use of emerging technologies throughout the airpower battlespace and with that, the need for the RCAF to procure compatible capabilities. These new capabilities require additional effort in defining specifications, test and evaluation, and training. When employed, they will encounter new technologies which may require the RCAF to rapidly develop tactics in response.

The problems due to the complexity of airpower were defined and the potential benefits from using constructive simulation were discussed. Constructive simulation could be used to support developing more precise requirements earlier by demonstrating capabilities of products that are under development. Constructive simulation could be used to begin test and evaluation and procedure development even before product development is complete.[248] It can increase training efficiency by providing CGF to exercise collaborative tactics.[249] Constructive simulation is not a direct solution to any of the airpower complexity problems but is a tool that can be used to generate a deeper understanding in a relatively short amount of time.

The progression of simulation technology within the aerospace industry and the RCAF and the current uses of simulation technologies demonstrated that the buy-in of simulation has steadily grown to the extent that the RCAF has doctrine in support of its uses and commander's guidance to increase the use of simulation.[250] The comprehensive

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[248] Colosi et al., 'ADS-33 Evaluation of the International CH-47 Chinook'.
[249] CAE Inc., 'Live-Virtual-Constructive (LVC) Training | CAE'.
[250] Canada. Department of National Defence, RCAF Simulation Strategy 2025.

existing inventory of simulators spans the RCAF fleets[251] and is supported by many RCAF personnel with varying and increasing education and experience with simulation. The conclusion was that the buy-in and inventory were both supportive of a constructive simulation capability.

A constructive simulation capability was then defined with four elements: the hardware, the models, the personnel, and the problems to solve. The interaction between those elements was demonstrated as a necessary component of the development of the capability. That interaction also suggested that the initial capacity of the capability must not be too ambitious as it is unlikely to be an off-the-shelf acquisition but would be a capability that would start small and then grow.

The GoC procurement processes and procurement models were considered to identify a model that may apply to procuring a constructive simulation capability for the RCAF. Each procurement model detailed in the policy[252] could work, but was not recommended for this project for two reasons, both related to the need for the capability to develop. First, the capability would not initially guarantee a viable solution to the complexity problem. A business case analysis needs to demonstrate a solution to a capability deficiency as being viable.[253] Second, the requirements must be specified in advance, but the capabilities will emerge from a needs-based development of the capability. Requirements could be amended but doing so is frequently a cause of cost overruns and suggests the new capability exceeds the true requirement.[254] A comparison

[251] FlightGlobal and CAE, 'Military Simulator Census 2020'.
[252] Canada. Department of National Defence, Project Approval Directive (PAD).
[253] Canada. Treasury Board, 'Directive on the Management of Projects and Programmes'.
[254] Canada and Office of the Auditor General, 'Acquisition of Military Helicopters.'

to the spiral development model used in software development[255] revealed similar benefits but was not a viable solution as it tended to generate costs and fail to achieve final results when used in requirements-based acquisition.[256]

A hybrid model of spiral development, cyclical projects, and the multi-project programme[257] that the author called a *Spiral Growth Model* was offered as a method to procure the constructive simulation capability. The proposed model would include three cyclical projects that spirally interact where the incremental outcomes of all three projects are considered in the requirements for the next cycle of each project. This procurement model allowed the interaction of the elements, allowed defining of achievable requirements for each element, and avoided forcing elements to advance when not yet supported in the interaction.

If a constructive simulation project does arise from this recommendation, and a spiral growth model is considered, it very likely will need modification. The saying, no plan ever survives first contact with the enemy,[258] is as true in procurement as it is in combat. The spiral growth model is one of perhaps many hybrid models that may be imagined. Regardless of the choice, each model must ensure the capability can develop the elements through their normal interaction.

It would be premature to define a project based on this analysis and thus bypass the formal processes,[259] but the analysis has identified important considerations. Education of RCAF personnel in simulation must increase. The use of a computer cluster

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[255] Boehm, ‘A Spiral Model of Software Development and Enhancement’.
[256] Gansler, Lucyshyn, and Spiers, ‘Using Spiral Development to Reduce Acquisition Cycle Times’.
[257] Canada. Department of National Defence, Project Approval Directive (PAD), 42.
[258] Helmuth Graf von Moltke, Moltke on the Art of War: Selected Writings (New York: Presidion Press, 1996).
[259] Canada. Department of National Defence, ‘Defence Purchases and Upgrades Process’.

in a secure facility should be procured. A capability that is established within four years, and then grows over eight years is feasible. Finally, the time to start this project is now.

This paper focused on a series of challenges in the RCAF that are linked to the inclusion of breakthrough technology into new airpower capabilities. Using the proposed *Spiral Growth* hybrid procurement model, this paper recommends procuring a constructive simulation capability immediately to support relatively simple airspace problems. It recommends that the capability is grown by ensuring suitable problems are identified and developed. With that growth, it will become a robust capability that will increase procurement efficiency, training quality, and operational flexibility.

Inaction will not make the problems with airpower complexity disappear. Inaction will allow project delays, cost overruns, and additional risks to continue to increase. Developing a robust constructive simulation capability will allow the RCAF to accelerate the inclusion of emerging technologies into new airpower capabilities. It will address the complexity.

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