A Discrete Event Simulation Tool for Conducting a Fleet Mix Study

Mikayla Holmes and Lise Arseneau
Defence Research and Development Canada (DRDC), Centre for Operational Research and Development (CORA), 60 Moodie Drive, Ottawa, ON, K1A 0K2, Canada

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Abstract: A fleet mix study is currently being undertaken by the Royal Canadian Navy (RCN) to determine the optimal composition of its future fleet to meet operational requirements. We introduce a Discrete Event Simulation (DES) model developed within the Operational Research Integrated Graphical Analysis and Modelling Environment (ORIGAME), called the ORIGAME Fleet Capacity Evaluation Tool (OFCET) that will be used to examine how well a proposed future fleet (number and types of naval platforms) meets the desired operational requirements to fulfill the Navy's mandate. This paper describes the OFCET in terms of inputs, outputs and assumptions and presents a case study with notional data to demonstrate how the tool can be used as part of a fleet mix analysis to answer "what if" type questions. Furthermore, extensions of OFCET and other problems that can be solved using this model will be provided.

1 INTRODUCTION

The Royal Canadian Navy (RCN) is currently undergoing the largest recapitalization of its fleet since the Second World War. To determine the optimal composition of its fleet to meet future operational requirements, a fleet mix study is being undertaken. Fleet mix studies are essentially a question of supply and demand: how well does a supply meet an operational demand? For the RCN, the supply consists of the type and number of platforms in the proposed fleet and the demand consists of several tasks and/or scenarios where the RCN would be expected to provide a response. In recent years, there have been comprehensive surveys and literature reviews on modelling and solving fleet mix-related problems (Wojtaszek and Wesolkowski 2012, Ali 2023). Due to potentially conflicting objectives, such as performance, deployability, availability, cost, and risk (Baykasoğlu et al. 2019), military fleet mix problems can be extremely difficult to solve.

Defence Research and Development Canada (DRDC)'s Centre for Operational Research and Analysis (CORA) has developed a fleet capacity evaluation tool to conduct the latest fleet mix study for the RCN. The tool was implemented in the Operational Research Integrated Graphical Analysis and Modelling Environment (ORIGAME), a Python-based open-source discrete event simulation (DES) interface available on a github repository (DRDC 2023). The model, named the ORIGAME Fleet Capacity Evaluation Tool (OFCET), builds on previous work, most notably Tyche (Eisler and Allen 2012) and the Platform Capacity Tool (Fee and Caron 2021). The OFCET is less computationally intensive than Tyche, where a single simulation run can take hours to complete (Eisler et al. 2014). Furthermore, OFCET is based on an open-source programming language, unlike the Platform Capacity Tool developed in Arena® software (Rockwell Automation 2024), and as a result the OFCET is less expensive and more flexible to modify. The OFCET has been designed to be flexible and adaptable, where the supply and demand are modelled as a deterministic and a stochastic process, respectively.

Following an overview of related work in Section 2, we will describe the OFCET in terms of the main inputs required to run the simulation, the outputs produced, as well as the assumptions and limitations of the tool in Section 3. A case study is provided in Section 4 using notional data to illustrate the type of "what if" questions that can be answered as part of the fleet mix analysis. Concluding comments including areas of future work are provided in Section 5.

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2 RELATED WORK

Fleet mix problems can be categorized as follows: determining the best fleet for a given interval of time; scheduling the acquisition and retirement of fleet platforms; or evaluating a particular fleet on a set of tasks or scenarios (Wojtaszek and Wesolkowski 2012). The latter problem is representative of the fleet mix study being undertaken by the RCN, where the scope involves performing multiple tasks using multiple types of platforms (increasing the complexity from a fleet mix study where a single task and/or a single platform is being assessed).

The determination of operational requirements (i.e., the demand) can be modeled as being deterministic or stochastic in nature (Fee and Caron 2021). When the demand is fixed based on wanting to achieve a certain level of ambition or by examining specific scenarios, the demand is deterministic. For example, a planning scenario for a conflict occurring on the Korean Peninsula was used to determine the effective mix of the US destroyer fleet (Crary et al. 2002) and a specified number of tasks to assign to different vehicle types was the demand to determine an Australian military vehicle fleet (Abbass and Sarker 2006). While operational requirements defined using a deterministic approach are concrete, it fails to consider the inherent uncertainty of international relations and potential threats (Lane et al. 2022). Furthermore, the RCN requested that the fleet mix be assessed against a wide range of tasks, including combat, patrol, search and rescue, and surveillance, each requiring the use of a variety of assets to provide a response.

In this paper, we will use stochastic simulation to determine demand where RCN operational requirements are represented by possible future timelines of vignettes (or scenarios), which can occur concurrently. The list of hypothetical vignettes represents the full scale of activities that would require the use of a naval platform, where each vignette can be characterized by type (e.g., peacetime or wartime), frequency, and duration, where all vignettes are distinct from one another. Several studies have estimated operational demand using a stochastic approach. As mentioned earlier, previous RCN fleet mix structure analyses were conducted using Tyche, where the demand is constructed stochastically from scenarios using frequency, start date, and duration inputs. The scenarios were randomly generated using a Poisson process or scheduled at known intervals (Eisler and Allen 2012). In another study, the RCN requested DRDC CORA determine the optimal number and types of platform modules to meet its mandate. A Monte Carlo discrete event simulation is used to generate the operational demand from 54 vignettes and a mixed-integer linear programming (MILP) model is used to determine the optimal mix of modules (Caron et al. 2019).

Other military applications where demand has been modeled stochastically include exploring ammunition stockpiles based on vignettes describing activities from several types of training and military missions that require ammunition (Caron et al. 2023), determining the fleet configuration of types of aircraft by modeling air mobility requirements from 127 different tasks over a one-year period (Wesolkowski and Billyard 2008, Wesolkowski and Wojtaszek 2012), and estimating operational demand from a set of 17 scenarios covering a full range of missions mandated by Canadian defense policy, with approximately 80 variants developed specifically to determine the force mix of personnel (Dobias et al. 2019).

Even though multiple platform types are being included in the RCN fleet mix study, the number of platforms in the proposed fleet to assess has been specified, making the supply deterministic. Each platform type has an operational cycle (OPCYCLE) which specifies when the platform is available to respond to tasks and when the platform requires maintenance. In order to maximize the number of platforms of a certain type available and minimize the number simultaneously in maintenance, the start of each OPCYCLE from asset-to-asset is offset to generate a schedule to accomplish these objectives. However, since the OPCYCLE for the proposed fleet are not known, the platform availability will be varied by examining a few different cases of maintenance profiles for each platform type.

3 OFCET

3.1 Overview

In its simplest terms, OFCET is a supply and demand model built within the DRDC developed DES environment named ORIGAME. The OFCET model, like its predecessor the PCT, attempts to allocate naval platforms (supply) to a stochastic operational demand which is generated over a specified timeline (Fee, 2024). The OFCET is written using an object-oriented programming (OOP) framework which gives rise to the model structure wherein objects of demand (vignettes) interact with objects of supply (platforms) based on various conditions and constraints. Figure 1 presents the steps that OFCET takes to progress from operational demand generation to platform assignment.

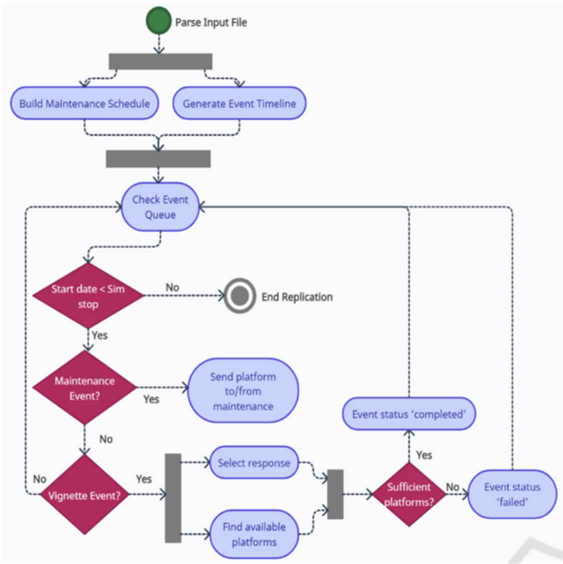

Figure 1: OFCET activity diagram.

The first step in the OFCET algorithm after the input data has been imported is to generate operational demand using vignette characteristics. The number of times an event occurs over the simulation timeline as well as its start date(s), depends on event type (random or scheduled) and frequency. For random events, a Poisson distribution is used to determine the number of events of that vignette type to be scheduled across the simulation timeline. A uniform distribution is then used to schedule the start date for each event. By default, this is set to assume equal probability of an event starting on each day of the simulation, however, it can be modified to only include a certain timeframe within the simulation (Fee, 2024). Equations 1 and 2 display the distributions and their respective parameters for random event scheduling.

$$\boldsymbol{f(k)} = \frac{\boldsymbol{e^{-freq*L_{sim}}(freq * L_{sim})^k}}{\boldsymbol{k!}} \tag{1}$$

$\boldsymbol{f(k)}$ = probability that k events occur across simulation
$\boldsymbol{freq}$ = historical frequency of vignette per year
$\boldsymbol{L_{sim}}$ = length of simulation

$$\boldsymbol{f(l)} = \frac{\boldsymbol{1}}{\boldsymbol{b-a}}, \boldsymbol{a \leq b} \tag{2}$$

$\boldsymbol{f(l)}$ = probability of start date on day $\boldsymbol{l}$

$\boldsymbol{a}$ = first day event can occur (Default=first day of simulation)

$\boldsymbol{b}$ = last day event can occur (Default=last day of simulation)

For scheduled event types, the number of events is determined for each year of the simulation using historical data. If the event occurs an even number of times per year it is scheduled accordingly. If, for example, an event occurs on average 3.2 times per year the model will schedule the vignette three times a year, 80% of the time and four times in a year, 20% of the time (Fee, 2024). Moreover, one can prespecify an interval of time in which a vignette is scheduled if the event must occur during timeframes throughout the simulation. For example, exercises in the Arctic may only be scheduled during the summer.

Duration and location of events are determined the same way for both event types. Duration of events is calculated using a triangular or uniform distribution depending on whether the minimum, mode (sometimes unavailable) and maximum parameters are known (Fee, 2024). The location of an event is chosen using a prespecified probability matrix that is based on historical data and subject matter expertise.

Maintenance schedules for each platform are generated concurrently to operational demand, but before the assignment process. All platforms have an OPCYCLE which specifies the timelines and sequence in which a platform is prepared to do certain tasks. During high readiness (HR) a platform can conduct the full spectrum of combat operations, while during normal readiness (NR) a platform is capable of employment to operations in permissive environments. The platform also goes into maintenance periods called docking or short work period (DWP or SWP) (Royal Canadian Navy, 2017). In terms of platform availability, DWPs have the largest impact, as some platform types are scheduled to be in maintenance for 18 months within a 6-year OPCYCLE, therefore the OFCET builds a schedule specifically for each platform class based on the DWPs only (but SWPs can be added if desired).

To minimize overlapping of unavailability amongst platforms of the same class, a staggered scheduling approach is taken following the methodology seen in previous fleet mix studies. The duration for which a DWP is shifted depends on the length of the OPCYCLE and how many assets the fleet contains of that class type. The maintenance module can also incorporate varying numbers of platforms by coast if desired.

For each replication, the simulation begins its assignment pipeline after demand and maintenance generation is complete. Since the OFCET is a DES, the state of the system is assumed to be constant between days in which an event appears on the event queue. Within the OFCET there are two types of demand which arise on the event queue – vignette events or maintenance events. Vignette events are prioritized within the event queue according to their consequence of failure. This measure goes from 1 – 'very low' to 5 – 'high' and is a prespecified input. Maintenance events have a priority value of 1000 so that all platforms go to or return from maintenance on a given day before a response is assigned to any operational demand. After each platform's availability is fixed for a given day, the OFCET looks at a variety of conditions to determine whether a response is possible for each vignette event.

The current version of the model does not consider platforms for assignment if they are on another event or in maintenance when a new event appears in the queue. For each platform available on day *x*, the OFCET assesses whether the platform:

i. Can get to the location of the event within the desired response time.
ii. Can complete the event and get back to home port before the next DWP.
iii. Has enough days left at HR if the event requires that level of readiness.

The platforms which satisfy these conditions are then compared to the vignette's chosen response option.

If the list of available platforms does not meet the requirements of the randomly chosen vignette response option, the event's completeness attribute is set to 'Failed' and the simulation proceeds to the next event. If, however, the available platforms meet or exceed the required response, they are then ranked based on the number of days the platform has left at HR as well as its respective travel time to the vignette location. If platforms within a certain class have different values for HR days and travel time, then the order of priority depends on whether the event requires HR. If a vignette requires HR, the platform(s) with the fewest days remaining at HR are assigned to maximize the utility of the platforms before they go down to NR. If the HR days are tied in ranking the platform with the shortest response time is assigned and vice versa. Lastly, the prioritized platforms are assigned, and their status becomes unavailable for the duration of the event plus two times their specific travel time. This process continues until an event appears on the queue which has a duration and response time which extends beyond the last simulation day, at which time the model replication is complete.

The four OFCET model output files and input file details are discussed below in Section 3.2 and 3.3.

3.2 Inputs

As mentioned above, the OFCET relies on several input parameters to generate the operational demand and platform maintenance schedules. Simulation specific parameters and platform attributes are also contained in the input file. One input file is required for OFCET which contains 6 mandatory worksheets. The worksheets are named *Vignette Information, Distance Matrix, Ship Information, OPCYCLE Parameters, Response List,* and *Simulation Parameters.* The following list provides a summary of what information is contained in each worksheet as well as the primary use of that information during the modelling process.

1. *Vignette Information*: contains type, annual frequency, duration parameters, response time, consequence of failure (1-5), HR (boolean) and location for each vignette and is used to generate operational demand.
2. *Distance Matrix*: Contains location names and IDs for all vignettes and the nautical miles from each location to the west and east coast RCN home ports – used to calculate platform travel time.
3. *Ship Information*: Contains ship class ID, name, home port, cruising speed and length of time at HR – used to allocate appropriate platform and time spent at HR.
4. *OPCYCLE Parameters*: Contains ship class, ID and number of assets, length of DWP and OPCYCLE – used to generate platform maintenance schedules.
5. *Response List*: Contains vignette ID and name, platform classes as columns and all combinations of allowed response options – used to assign platforms to vignette events.
6. *Simulation Parameters*: Contains length of simulation (years) and event run on length – used to define model and event lengths.

3.3 Outputs and Post-Analysis

Modifying output specifics to the OFCET is a simple task due to the user-friendly and flexible nature of ORIGAME. The current iteration of the OFCET is built to output four files which provide information on: the operational demand generated, platform allocation, response option distribution and a history log that documents reason for failure of any event.

The structure of the output files depends on which mode the simulation was run inside ORIGAME. Since all simulations use the batch mode, it will be discussed here. When running a batch mode, simulation averaged metrics can be obtained, and the stochastic nature of event generation is exemplified. As such, ORIGAME builds a SQL database file for batch runs which has four tables named *History, RespData, eventData* and *shipData*. The database files must be processed using an integrated development environment (IDE) to calculate averaged metrics. Some of these could include event completion rate by vignette or overall, distribution of platform demand generated by the random response options, and the average number of HR events on any given simulation day. These metrics (among others) provide useful insight into how well the fleet is meeting its operational demand.

The following case study aims to provide clarity on the benefits of these output types and the overall flexibility of the OFCET as a naval planning tool.

4 CASE STUDY

4.1 Assumptions

Before outlining the case study details and results, some assumptions and caveats will be presented. It is important to note that unlike previous fleet capacity tools, these caveats are not necessarily permanent. Modifications of the OFCET can be implemented as required since it is based in an open-source programming language (Python) and not hindered by any licensing or software restrictions.

The OFCET caveats which are discussed below:

i. No re-assignment of platforms when away from home port.
ii. Time at HR for all platforms modelled optimistically.
iii. No SWPs incorporated into maintenance schedule.

Re-assignment pertains to the functionality where a platform can be re-tasked to a higher priority event while currently assigned to an event. This capability may represent reality more accurately, however, the output files which keep track of why events have failed do not indicate a pressing need to add this into the current version of the model.

Platform readiness levels for the RCN, both duration, time frame and type, are defined in each platform's OPCYCLE. For this case study, the platform availability has been modelled optimistically because we have not included SWPs in the maintenance profiles. Furthermore, platform readiness levels have been modelled optimistically as well. The platform goes to HR for the first time when an HR event occurs after the platform has finished a DWP. The platform then remains at HR for a set number of days (can be different for each platform or class) regardless of whether it is assigned to HR or NR events during that time. After those days have lapsed, the platform must come out of a DWP before it can go back to HR which accurately represents the real-life platform readiness cycle.

The last assumption to be discussed relates to the way response options are decided on. A vignette can have many acceptable combinations of platforms that can complete it. Whether an assignment is possible or not requires comparing the platforms available to those acceptable response options. The OFCET currently selects a response option randomly with equal probability across options since running batch simulations with many replications allows for all options to be selected and compared. The following subsections will outline a fleet mix study conducted using OFCET with notional data.

4.2 Inputs

The notional fleet mix study presented here exemplifies the primary use case for the OFCET model. Specifically, the OFCET was used to assess how one RCN fleet composition meets three different cases of demand. For each of these cases (outlined below), the operational demand is generated, and platforms are assigned the same way; however, each scenario has a different (not mutually exclusive) set of maritime events for which the fleet is assessed against. It is important to note that the OFCET can also be generalized to solve workforce supply and demand problems for army and air force as well as assist in decision making processes regarding impact of maintenance period times or demand requirements.

Recall, from Section 3.1, that all operational demand is generated according to vignette characteristics. Historical data and discussions with subject matter experts (SMEs) can also provide qualitative information which enhances the modelling approach taken here (Dobias et al, 2019). The historical data can also provide information about the realistic concurrency between vignettes.

Concurrency of events is a challenge to consider within fleet capacity tools. It is imperative to assess naval capability based on future timelines of operational demand that are as realistic as possible; however, this is difficult to emulate when the demand includes all events the fleet could undertake. For example, day-to-day operations like a public engagement event would be quickly halted if a search and rescue or full spectrum operations event occurred requiring a naval response.

One way to limit the impact of demand concurrency is to define categories: wartime (WT), peacetime (PT), discretionary (D) and non-discretionary (ND) for each vignette based on the type of operation it involves. Categorization allows for input files to be scoped down into wartime or peacetime scenarios and thus minimize unrealistic concurrency of operational demand. Ideally, this scoping will also allow the overall fleet capacity metrics to more accurately express how well the demand is met.

Three demand cases are explored here using the OFCET model. They are the full, peacetime (excludes WT) and wartime (excludes PT and D) scenarios. The total number of vignettes are 63, 44 and 26, respectively. Table 2 contains a subset of 4 notional vignettes with their input format for reference.

Table 2: Subset of 4 notional vignettes and characteristics.

			Duration (days)		
ID	Category	Frequency (annual)	Min	Mode	Max
2	WT	0.5	30	227	730
5	PT	6	7	NA	50
11	ND	0.07	10	35	60
40	D	1	30	NA	30

The supply for the notional fleet mix study is predetermined and consists of four classes of platforms with a different number of assets within each class. Additionally, each class has a specific OPCYCLE and predetermined length of time in maintenance which impacts the overall supply. These details are presented in Table 3, followed by Section 4.3 which goes over various metrics used to assess how well our supply met the operational demands for all three cases.

Table 3: Supply for notional fleet mix study.

Class	No. of Assets	Length of OPCYCLE	Months in DWP
A	10	5 yrs.	12
B	5	5 yrs.	15
C	7	6 yrs.	18
D	2	6 yrs.	6

4.3 Results

All results are derived from the OFCET model running over 80 replications with a simulation length of 13 years. One year burn-in and cool-down periods are used and therefore all metrics presented come from data across 11-year timelines. These adjustments are necessary as platforms are not prepositioned on events or in maintenance when the simulation begins and similarly platforms will not be assigned to an event if the end of that event surpasses the simulation timeframe. For the case study 80 replications was sufficient and takes less than 15 minutes to complete for the full demand input file. The wartime demand case with only 26 vignettes, completes in six minutes, which highlights improvement on long computation times seen with the previous fleet capacity tool Tyche.

Typically, with supply and demand models, the first metric looked at is overall event completion rate. Within the framework of fleet capacity and any defense related capacity model there are multiple factors and interactions at play which must be considered in addition to overall event completion. These factors and their impact are emphasized by an example, discussed below with aiding information in Table 4.

To illustrate, consider a randomly generated timeline that contains an instance of vignette ***2*** which requires a multi-platform response, all of which must be at HR for a duration of 6 to 8 months. The completion of this event can have a large impact on whether many occurrences of a shorter, less demanding vignette, for example ***5***, gets completed over that same time frame. In this example, an overall event completion rate which averages out the failure of many instances of vignette ***5*** with one completion of vignette ***2*** can miss these nuances entirely.

Table 4: Response options and HR requirements for vignettes discussed in previous example.

		Platform Class			
ID	HR	A	B	C	D
2	Yes	3	2	0	1
5	No	0	0	0	1

For the case study being discussed here, a variety of metrics will be shown to demonstrate the type of results that can be obtained from the OFCET. First, the overall event completion rate for all three demand cases is shown in Table 5. To gain further insights into how well the supply meets some of our wartime demand, Figure 2 displays the average event completion rate for 14 of the 26 vignettes. Figure 2 also illustrates how the overall event completion rate is unable to capture the large variation in event completion for individual vignettes and the importance of investigating vignette specific completion rates.

Table 5: Overall event completion rate for three demand cases.

Demand Case	No. of Vignettes	Overall Event Completion
Full	63	70%
Peacetime	44	73%
Wartime	26	75%

An additional function of the OFCET model is that for any demand scenario, the user can specify that they want only the event timeline to be generated, which means no assignment phase will occur. Figure 3 displays one possible timeline generated using the 26 vignettes within the wartime demand case. Although these analyses of the OFCET outputs do not explore how much of the demand is currently met with a specified fleet, it can be used to inform naval planners about the potential requirements for certain platform classes and/or lengths of time needed at HR. Additionally, looking at the various platform response options for certain demand cases can assist in identifying how commissioning or decommissioning a platform class will impact the overall fleet's ability to meet operational requirements.

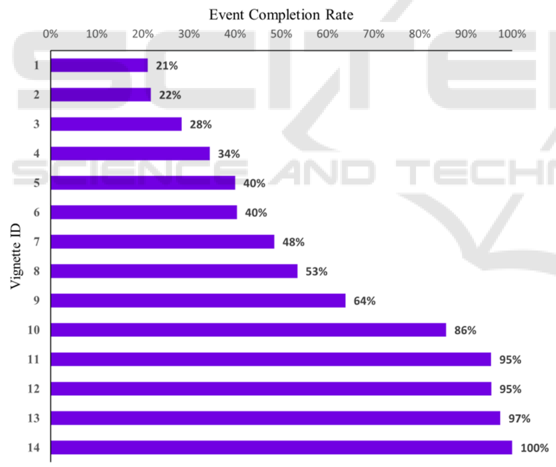

Figure 2: Event completion rate of 14 vignettes from the wartime demand case.

In summary, the results of the notional fleet mix study presented above demonstrate useful metrics and information one can acquire through use of the OFCET. Overall event completion rates across the three demand cases increased slightly as the number of included vignettes decreased, however, careful consideration is required when looking at one aggregate metric. Average event completion rate for individual vignettes provides a greater degree of certainty towards how well the fleet can meet operational demands. Additional outputs, such as event failure logs, also aid in providing naval personnel with explanations regarding specific vignettes completion rate. These outputs emphasize areas where the model can be improved to more accurately represent naval scenarios.

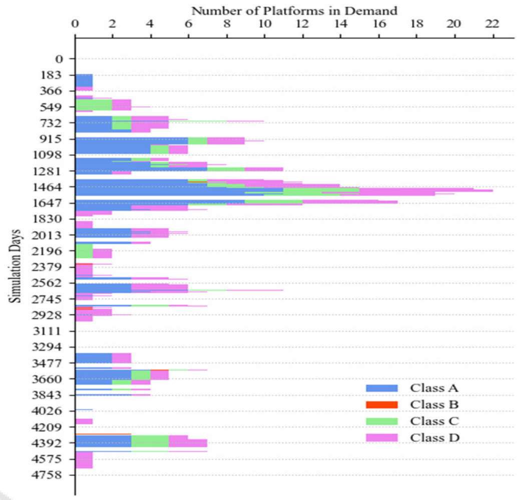

Figure 3: 13-year operational demand of each platform class for wartime case.

5 EXTENSIONS

One benefit of the OFCET model being based in a DRDC tailored, open-source platform is the opportunities for improving and adding new modules to the model. Some of these potential modules could:

- Re-task platforms.
- Incorporate an optimization algorithm.
- Build commission and decommission functionality.
- Incorporate platform attrition.
- Add in crewing and/or training component.

In general, it is valuable to incorporate aspects of the RCN functionality into fleet capacity tools to provide the most useful results to decision makers. Re-tasking platforms would mimic the real-life scenario in which a platform is originally assigned to an event but gets re-assigned to a new, higher priority event in a nearby geographical area – i.e. a search and rescue mission. These demands are often sporadic in nature and can be investigated by using the current OFCET version and assessing information within the event history output files.

Incorporating previous work done by Widmer (2024) and Fee (2019) would allow for maintenance schedules to be optimized and can easily be incorporated into the OFCET due to its Python framework.

The OFCET could also be extended to deal with platform transitions and their effect on the RCN fleet capacity. Moreover, army and air force services could utilize the platform specific approach of the OFCET to assist in understanding how their resources meet operational demands. The general workforce modelling approach within the OFCET can be adapted for many problems outside of naval fleet procurement.

6 CONCLUSION

This paper presents a new fleet capacity evaluation tool along with a notional fleet mix study to display the OFCET's functionality. The OFCET model is not computationally taxing and is flexible, which improves upon the limitations of previous fleet capacity tools such as PCT and Tyche. It is based in the DES framework of ORIGAME which improves its longevity due to having fewer licensing and software constraints. The OFCET provides various outputs that can be used to investigate questions asked by stakeholders, naval planners and other services alike. This information assists in informing how certain fleet composition(s) can meet RCN operational demands. The OFCET is easily adaptable and can be implemented as required to address subsequent RCN questions, or more broadly, defence supply and demand problems.

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