Simulation of the Deployment of Forward Arming and Refuelling Points for Decision Support

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ABSTRACT

Forward Arming and Refuelling Points (FARPs) play a crucial role in supporting aircraft operations by facilitating deep penetration into enemy territory and ensuring sustained presence in the area of operation. The logistical units responsible for establishing FARPs face the challenge of timely deployment, since the necessary equipment must be on-site and operational before the aircraft arrive for resupplies. A crucial element in FARP operations is thus the selection of suitable locations, and taking into account the time that is needed to get there by truck. M&S enables the exploration of different options during the planning phase of FARP operations.

The contributions of this paper are threefold. First, an initial model of the relationships between the factors surrounding the success of FARP operations is presented. Second, a simulator prototype is constructed based on the model, consisting of Monte Carlo simulation to quantify associated risks and discrete event simulation to simulate the time aspects of such operations. The simulator is implemented as a Python-based simulation program that interprets real-world map images, simulates FARP operations, and generates data such as helicopter fuel consumption and FARP survival probability. Third, the use of the simulator for decision support regarding the deployment of FARPs is demonstrated in two use cases.

1.0 INTRODUCTION

Aircraft stationed at Forward Operating Bases (FOBs) are not always in a convenient position to take off, perform their mission in the area of operations (AOO), and return to the same FOB on exactly one tank of fuel. Needing to return to the FOB for refuelling, as well as rearming and possibly swapping crew members, requires transit time that is better spent performing operationally relevant activities. Forward Arming and Refuelling Points (FARPs) are temporary ground-based service stations for rearming and refuelling aircraft, as well as allowing crew swaps in the field. Placing FARPs close to the AOO allows for a faster turnaround time of aircraft, and thus for a higher effectiveness during sustained operations.

The placement of FARPs remains an art rather than a science. Placing a FARP near the AOO may increase the operational effectivity of the aircraft that it services, but also makes the FARP itself vulnerable to ranged threats coming from the AOO. Furthermore, setting up the FARP requires time and effort (e.g., sending trucks with the necessary equipment to the desired location), while the need for the FARP may only just have become evident during the planning of the next mission. This way, while a FARP near the AOO may be desirable for the next mission, there might not be enough time left for the equipment to physically arrive in that area. The placement of FARPs, like many operational concepts, is therefore essentially a continuous balancing act between what is desirable, what is necessary, and what is possible – viz. the ‘ends, ways, and means’.

The aim of this paper is to investigate the use of a FARP deployment simulation in order to support the decision-making process of the FARP mission planner. FARP mission planners have to process large quantities of information (e.g., mission plans, terrain information, and tactical situation reports) in a short timeframe, making it a bottleneck in the overall helicopter mission. This is especially the case when FARPs are deployed using trucks. For example, if a truck has to drive through a dense forest in order to reach the FARP location, then this can take a significant amount of time in the FARP mission planning and execution. In the meantime, the helicopters are not obstructed by different types of terrain and can therefore consistently be on time at the FARP location.

M&S is well suited to analyse large quantities of data. Therefore, by simulating key processes of FARP mission planning during the air tasking order development, important data can be generated about the upcoming FARP operation. The simulation results are expected to help the FARP mission planner make decisions on e.g., FARP placement and the smart use of available assets. Despite the capabilities offered by the use of FARPs, they have received little attention in the M&S literature.

This paper considers FARPs in the context of rotary wing operations of the Royal Netherlands Air Force (RNLAF), which operates both transport and attack helicopters. The RNLAF has shown a renewed interest in FARP operations (Beveren, 2018; Snel, 2022; Marchand, 2022; Martin, 2022). The use of FARPs allows the RNLAF, a relatively small air force, to maximise the operational use of its assets. A proper application of M&S in this area may thus prove to be a force multiplier. Therefore, the research question that this paper aims to answer is as follows: *"To what extent can simulation support the decision-making process of FARP operations?"*.

Working toward a decision support application, this paper first captures the factors relevant to FARP operations in a model, after which a simulation framework is developed. The contributions of this paper are as follows. After a brief introduction of FARP operations and related work (section 2), the simulation framework that was developed in support of this research is described (section 3). Next, two use cases are presented by which the application of the simulation framework is demonstrated (section 4). Finally, the outcomes of the two use cases are discussed and the paper is concluded (section 5).

2.0 FARP OPERATIONS

FARPs have a long history. They can be traced back to World War II, when German pilot Hans Rudel strategically positioned ammunition and fuel stocks in forward locations on the battlefield to extend his sphere of influence (Rudel, 1958). These forward placed stocks enabled deep attacks into enemy territory. In more abstract terms, the primary objective of FARPs is to furnish commanders with rapid resupply capabilities for their units, enabling them to sustain their operations (Reeves, 1993). The term FARP encompasses a range of concepts that can be applied to different types of operations. At the end of the twentieth century, Reeves (1993) associated FARPs with the support of mechanized infantry, while modern United States technical procedures (US Department of Defense, 2018) associate FARPs with the support of military aviation units.

Today, FOBs are often used to station units when military operations are conducted outside of national borders. Ideally, these FOBs would be placed close to the AOO since this would make the logistical chain to support frontline troops shorter and therefore more efficient. However, with the development of long-range striking capabilities, the FOBs and their supply lines are under threat of enemy fire. This is observed during the ongoing Russo-Ukrainian war, where Ukrainian armed forces are able to put the logistics of the Russian armed forces under threat with long-range weapon systems such as the HIMARS (Zabrodskyi et al., 2022). The use of temporary FARPs is one way to prevent such situations.

The Netherlands Air and Space Operations doctrine mentions the use of Forward Refuelling Points (FRP) by the United States Army in Operation Desert Shield in 1990 (Royal Netherlands Air Force, 2014). However, no further use of FRPs or FARPs are mentioned in the doctrine. Also, the general doctrine of the Netherlands Armed Forces (2019) does not mention the employment of FARP operations. Still, recent exercises by the RNLAF such as Falcon Autumn 2022 have shown an increase of interest in training FARP operations (Snel, 2022).

FARPs can be established via aerial or ground units. Aerially established FARPs use aircraft to transport the fuel and munition to the FARP location. For example, a Chinook helicopter can be equipped with fuel tanks that can be used to refuel other aircraft (Sangster, 2020) or M1 Abrams tanks (Dougherty, 2023). The Chinook would land at the FARP location to then act as a non-moving, on-the-ground refuelling point. While aerial delivery of FARPs is fast and not limited by roads or terrain features, it does tie up valuable aviation assets and can increase the probability of detection by enemy surveillance efforts (Marine Corps Techniques Publication MCTP 3-20B, 2016). The need for aviation assets is proportionally a larger challenge for smaller air force organizations such as the RNLAF.

The opposite is true for ground delivery of FARPs, which is flexible, easy to coordinate, ties up less valuable resources, but is also slower in reaching the FARP location and limited by roads and terrain features. It is vital that the ground FARP units can start their journey to the FARP location on time in order to ensure that the aircraft can be armed and refuelled on time. If these FARP units would start their operation at the same time as the aircraft moving to their AOO, then the FARP units would most likely arrive too late at the FARP location to conduct their arming and refuelling process. The RNLAF possesses new Scania Gryphus transport trucks which have a higher loading capacity and better road performance compared to the previous DAF trucks, and have the capability to be quickly fitted with an armoured cabin (Dutch Ministry of Defence, 2021) for increased survivability in contested environments.

As mentioned above, there are different perspectives one can take on FARP operations. The US perspective on FARP operations might not always reflect how FARP operations are conducted by other western countries. For example, Gill and Day (2021) describe a US ‘Super-FARP’ concept which refuelled 96 helicopters in 43 minutes. Conducting FARP operations in such numbers is not realistic for most other western countries (e.g., the RNLAF currently has 79 helicopters total). Furthermore, the US Armed Forces have conducted research on dispersed FARP operations for fixed-wing aircraft, as discussed by Davis (2014) and Owen (2018). Interesting developments related to dispersed FARP operations that include non-helicopter platforms in high-readiness operations are discussed in works such as those by Mahaffey (2022) and Sangster (2020).

3.0 SIMULATION FRAMEWORK

This section describes the development of a simulation framework for FARP operations. Below, we briefly discuss our model of FARP operations and the parts of this model that we include in the newly built simulation (section 3.1). Next, we outline the foundations of the simulation framework (section 3.2), including how FARP locations are analysed in the simulation (section 3.3), and how the simulation is executed (section 3.4).

3.1 A Model of FARP Operations

The simulation of FARP operations requires a model by which the preconditions and effects of FARP operations can be understood. In brief, successful FARP operations extend the potential reach of a helicopter, make available ammunition for the helicopter, and grants the possibility to replace the helicopter crew. The reach, ammunition, and fresh crew increase the likely effectiveness of the military operation. In this section we formalize our understanding of FARP operations in order to enable simulation of these operations.

Figure 3-1 shows the preconditions for and effects of successful FARP operations as a directed graph.

Inspired by a model known as the Fuzzy Cognitive Map (FCM), each edge of the graph shows the effect (+ positive or − negative) that the source factor has on the target factor. True FCMs allow for dynamic calculations by assigning a numeric strength to each factor, and using the edges to propagate the strength values throughout the graph. However, for the current research we chose to focus on the actual movement of trucks and helicopters to gain more understanding of the effects these factors have on each other.

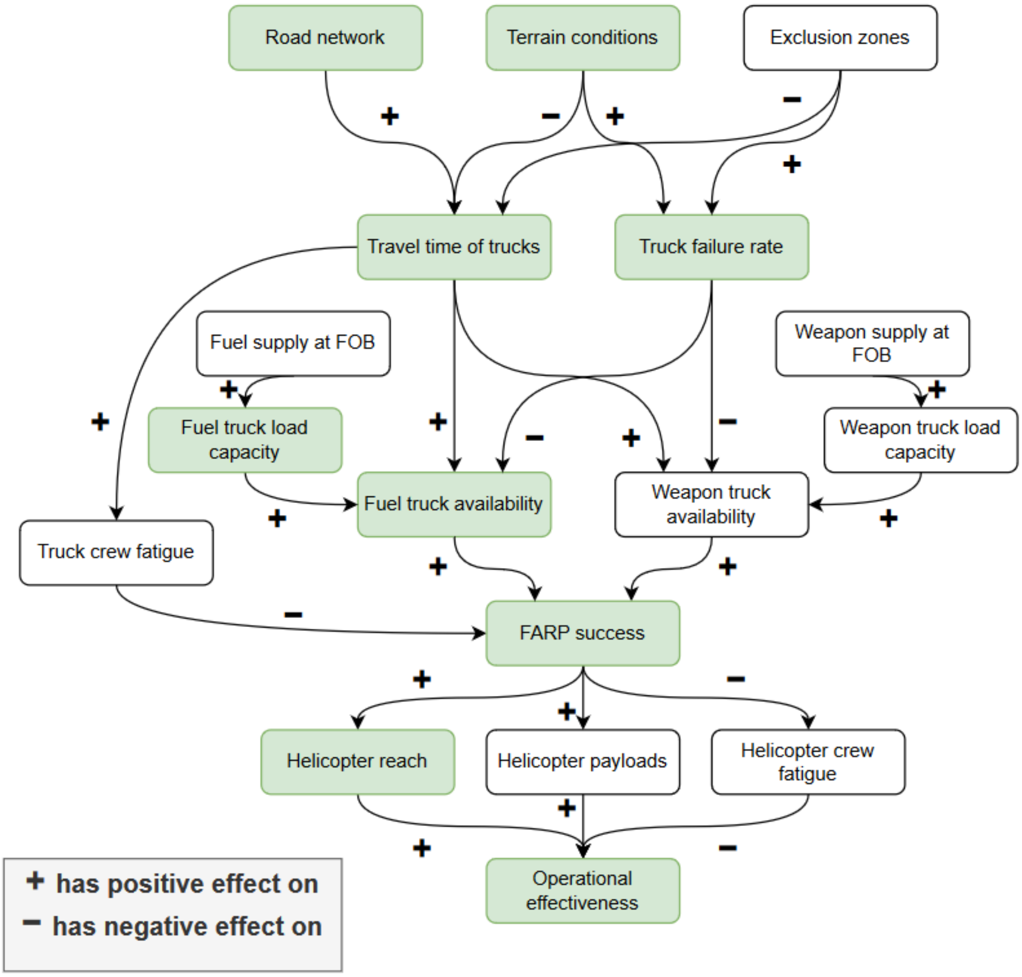


Figure 3-1: FARP operations model showing preconditions for and effects of successful FARP operations. Green factors show the reduced version of the model.

The effects of a successful FARP operation (middle of Figure 3-1, *FARP success*) are increased *Helicopter reach*, increased *Helicopter payloads*, and decreased *Helicopter crew fatigue*. Together, these three factors contribute to increased *Operational effectiveness*. *FARP success* is achieved by *Fuel truck availability* and *Weapon truck availability*. The *Fuel/Weapon truck availability* depend on the *Travel time,* their *Load capacity,* and the *Truck failure rate.* Also, FARP trucks require the correct *Fuel/Weapon supplies at FOB.* Naturally, *Travel time of trucks* leads to *Truck crew fatigue*. *Road network, Terrain conditions,* and *Exclusion zones* influence the *Travel time of trucks* and the *Truck failure rate*.

For the first version of the simulation framework we consider a reduced model targeted at the refuelling function of FARPs. The motivation for this reduced model is to showcase the value of this simulation framework for decision-support application, while keeping the complexity as low as possible in the current stage of development. The refuelling function was prioritized since every helicopter needs fuel, while not every helicopter needs ammunition. The reduced model is shown in Figure 3-1 using the green highlights.

3.2 Simulating FARP Operations

The concept consists of a simulation environment, based on the model of FARP operations (section 3.1) in which FARP mission planning and execution can be simulated. The simulation aims to support the FARP mission planner by analysing feasible FARP locations (see section 3.3), and identifying the logistical requirements for the mission (see section 3.4). While the location analysis is done on a tactical level, the identification of logistical requirements for the whole mission is done on an operational level. The simulation therefore functions as a bridge between the tactical and operational level. Lastly, the simulation can be used in a CD&E context to determine the effects of new operational concepts.

The real world is represented in the Python based simulation framework by a square area of 768 by 768 pixels. The FOB is placed at the location [1, 1], which is the bottom left of the area. The AOO is placed at the location [768, 768], which is the top right of the area (see Figure 3-2a). The distance between locations is calculated using the Euclidean method. The distance a helicopter would fly between the FOB and AOO is approximately 1082.41 units in the simulation framework.

Generally speaking, the further a FARP truck has to drive, the more time the truck spends in a vulnerable position, and thus the higher the chance that something happens to the truck that prevents it from setting up the FARP. In the simulation, the Monte Carlo method is applied to calculate the probability of FARP trucks reaching their destination and setting up the FARP, which we refer to as the *survival probability*. The survival probability of each truck aims to capture the element of risk inherent to setting up a FARP. For each simulated FARP placement the simulation uses the survival probability to determine whether the truck has survived its journey to the FARP location. In case of dispersed FARP operations, an average survival probability is calculated of each FARP combination. Discrete event simulation is applied to simulate the time aspect of FARP operations, i.e. the time taken by helicopters to fly to the AOO and back to the FOB via a FARP.

3.3 Location Analysis

The objective of the location analysis is to find feasible FARP locations. The helicopters have to be able to land at the FARP location which means that the terrain conditions have to be favourable. Ideally, a detailed Geographic Information System (GIS) would be used since this offers accurate terrain data. However, implementing such a system requires a significant amount of time and resources, and is not the goal of this paper. The work by Erskine et al. (2022) and Kroh (2020) show how GIS can be utilized for helicopter landing zone detection. For the current work, it is assumed that the demonstration of a simulation application for decision support does not depend on the level of realism of the location analysis.

In the simulation framework, location analysis is performed based on the graphical representation of terrain maps obtained from *OpenStreetMap* (http://www.openstreetmap.org). The location analysis method looks at a section of the map and awards points based on the colour of the pixels according to a scoring system. This scoring system is designed to highlight desirable areas such as roads and fields. For example, dark green pixels represent a forest, which is an undesirable location for a FARP and therefore gets no points. Light green pixels represent a meadow, which would be more desirable and therefore gets points. Roads are identified as highly desirable and are therefore granted the most points. The scoring system is a registry with colour codes which each have their own amount of points, see Table 3-1.

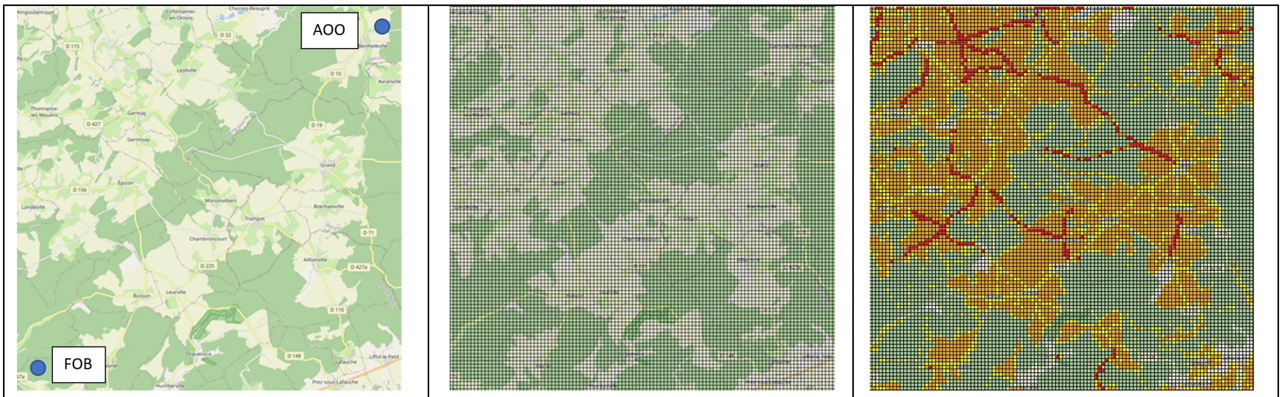
Table 3-1: Scoring system used by the FARP location analysis.

Colour	Type	Points
Light green	Meadow	0.5
Light grayish yellow	Farm Field	0.5
White	Road	4
Light yellow	Road	4

To account for the scale of the map, a grid is drawn over the map, see Figure 3-2b. Each grid square represents a possible FARP location. The colours of the pixels in each grid square are rated according to the scoring system, and are summed up to form a total score for the square. The total score for each square is used to determine a desirability of a FARP location, see Table 3-2. Figure 3-2c shows the highlighted squares according to the scoring system. Currently, the scoring system only identifies the map colours used in western Europe in order to limit the complexity of the scoring system. Other parts of the world are geographically very different compared to western Europe and therefore use different colours and markings on the map. For example, desert, swamp, and jungle environments are not registered in the scoring system.

Table 3-2: Desirability of grid squares resulting from the FARP location analysis.

Sum of points for square	0-4	5-15	16-25	26+
Desirability	None (No colour)	Low (Yellow)	Medium (Orange)	High (Red)



(a) (b) (c)

Figure 3-2: Location analysis performed on example mission area in France. (a) Map downloaded from OpenStreetMap. (b) Grid overlay placed on the map. (c) Each grid square is assigned a colour based on the number of points assigned to the pixels in each square.

3.4 Mission Planning & Execution

For each location for which the location analysis has been performed (see section 3.3), a series of helicopter missions is planned and executed. In the current study, only highly desirable (red) locations are eligible. Each mission is planned for and flown by three generic helicopters. The helicopters fly their mission in the simulation from the FOB, to the AOO, to a FARP, and back to the FOB. The helicopters consume a certain amount of fuel each time step and are therefore not able to fly around infinitely. At the FARP the helicopter is able to replenish its fuel, which takes one time step. The speed of each helicopter, the fuel consumption of each helicopter, the fuel capacity of each helicopter, and the fuel capacity of each FARP are modelled as constant numerical values, tuned proportionally to each other to represent real-world cause-and-effect in the simulation. The output of the simulation is a table where, per FARP combination and per time step, the following data is recorded: the location history of each helicopter, the locations of the FARPs, the distance from the FOB to each FARP, the fuel consumption of each helicopter, the fuel supplied by each FARP and the survival probability of the FARP.

A distinction is made between dispersed and non-dispersed FARP operations. In dispersed FARP operations, three FARPs are deployed. The simulation calculates all the possible combinations of three FARP locations that can be made from the eligible FARP locations resulting from the location analysis. From this set of combinations, one thousand combinations are randomly sampled to limit the computational time required. In non-dispersed FARP operations, a single eligible FARP location is randomly selected from the FARP locations resulting from the location analysis. If a helicopter occupies a FARP at a certain time step, that FARP becomes unavailable for other helicopters. This is done to force the helicopters to choose different FARPs, which is an essential part of dispersed FARP operations. This restriction is lifted for non-dispersed FARP simulation, making it possible for a single FARP to facilitate multiple helicopters at the same time. The fuel needed to reach the FARP and the availability of the FARP determine if the mission planning for the helicopter will be successful or not. In case one of the two requirements is not met, the mission planning fails, and the helicopter does not start its mission. When the mission planning has been successful, the helicopters starts moving to their planned locations sequentially.

4.0 DECISION SUPPORT USE CASES

In this section, we describe the application of decision support for a hypothetical FARP mission planner who investigates (1) helicopter fuel consumption and FARP survival probability, and (2) the impact of dispersed/non-dispersed FARP operations on fuel consumption. The application makes use of the simulation framework described in section 3.

The two use cases are presented from a FARP mission planner’s perspective and reflect possible decisions a FARP mission planner might need to make. Essentially, the relations between the key factors of FARP operations are tested. It is assumed that applying statistical analyses to the results of the simulation may support the decision-making of the FARP mission planner. In the following two use cases the simulation is used to find suitable FARP locations in five different example environments: one randomly selected area in each of France, Belgium, Germany, the Netherlands, and Spain.

4.1 Use Case 1: Trade-off Between Helicopter Fuel Consumption and FARP Survivability

Fuel is one of the vital resources necessary to use helicopter assets. Reducing helicopter fuel consumption could reduce the logistical load for a military operation. Placing a FARP close to the AOO reduces the flight time for a helicopter to reach the FARP and therefore reducing its fuel consumption. However, increasing the distance the FARP truck has to drive also increases the time the truck spends in a vulnerable position. In this first use case, the FARP mission planner is going to investigate if there is a trade-off between helicopter fuel consumption and FARP survival probability. It is expected that a long driving distance for the truck lowers its survival probability, but at the same time benefits helicopter fuel consumption.

To investigate this trade-off, 5000 dispersed FARP placements were simulated. Figure 4-1 shows the relationship in a scatter plot. A Spearman correlation coefficient was computed to assess the monotonic relationship between the helicopter fuel consumption and FARP survival probability using a confidence interval of 0.95. A negative correlation between the two variables was found, $\rho(4998) = -0.163$, $p < 0.001$, indicating that as FARP survival probability drops, helicopter fuel consumption increases.

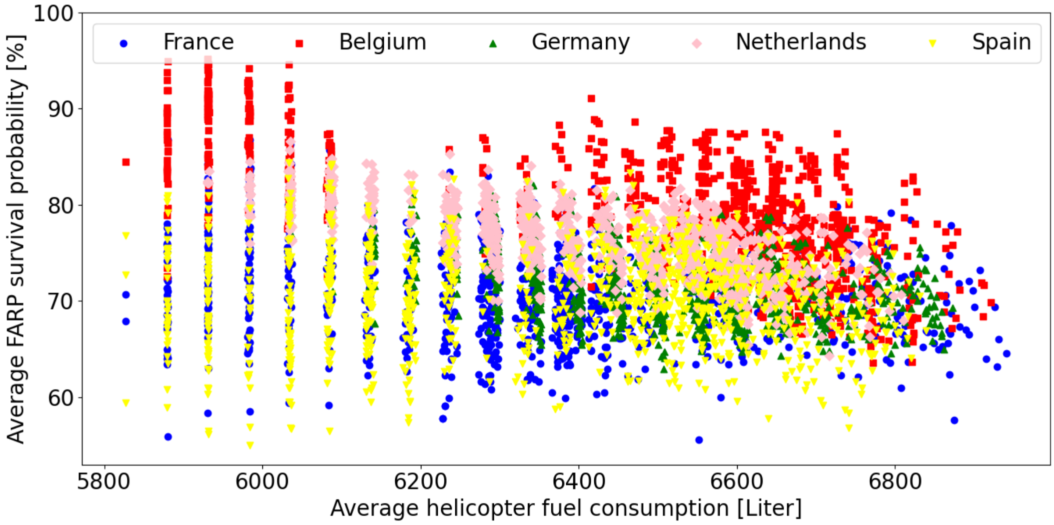


Figure 4-1: Scatter plot showing helicopter fuel consumption versus FARP survival probability.

The simple trade-off that we expected to see is not reflected in these results. The reason is likely that this trade-off holds while only planning FARP locations directly on the flight path between the FOB and the AOO. However, the simulation considers FARP locations in a square area around the FOB and the AOO (see section 3.3). FARP locations in the extreme corners (northwest and southeast of the flight path) lead to long driving distances for the trucks, but also to substantial detours for the helicopters. In Figure 4-1 the results for Belgium show a clear division between FARP locations with a high survival probability and low fuel consumption (upper left of the figure, likely on or near the optimal flight path), and FARP locations with a low survival probability and high fuel consumption (lower right of the figure). The results are consistent with the lay-out of the desirable FARP locations which were used in the simulation (see Figure 4-2). Therefore, the simulations appear to be robust with regard to the various input areas that were used.

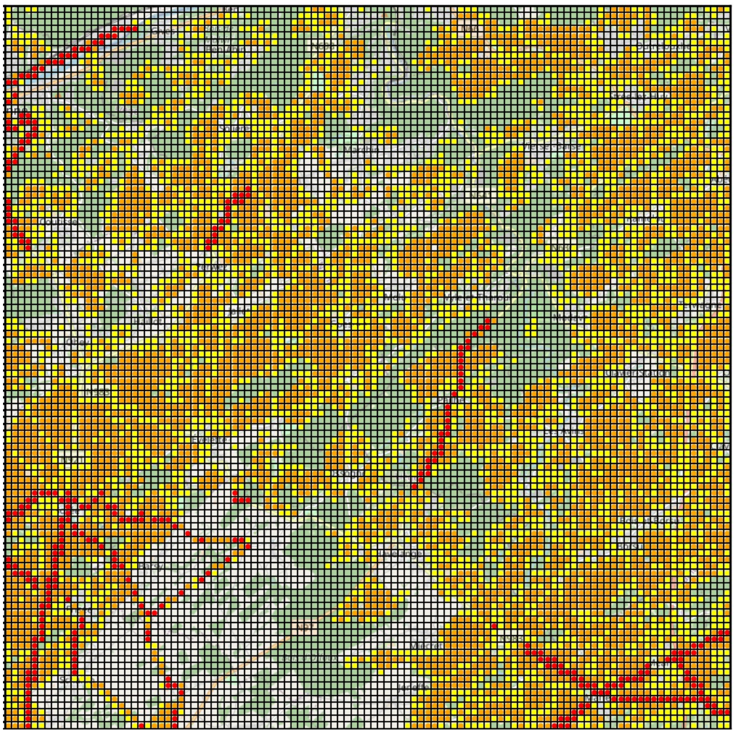


Figure 4-2: Desirable FARP locations in the example area in Belgium.

An interesting pattern can be seen in Figure 4-1. We believe this pattern is the result of the use of Euclidean distance measure in this simulation, together with fuel consumption being a function of distance flown. Regarding fuel consumption, the optimal placement of a FARP is on the flight path that is the diagonal from the FOB to the AOO (see Figure 3-2a). As FARPs are placed further from the optimal flight path, the number of possible deviations via a FARP increases, and because of the Euclidean distance measure, the variation in total distance flown (and thus fuel use) increases as well. Thus, the more FARPs are placed away from the optimal flight path, the more the data points are evenly scattered in Figure 4-1.

4.2 Use Case 2: Fuel Use in Dispersed Versus Non-Dispersed FARP Operations

Dispersing FARPs prevents creating a singular high value target that an opponent force could strike with long-range weapon systems. However, this could increase the distances the helicopters have to fly in order to reach each FARP. In the second use case, the FARP mission planner is going to investigate the impact of dispersed FARP operations on helicopter fuel consumption. Knowing whether this is the case, may enable smarter logistical planning throughout the entire operation with regard to the fuel management.

For this use case 6500 FARP placements (of which 5000 dispersed and 1500 non-dispersed) were simulated. Student's t-test was used to determine whether there is a significant difference in fuel use in dispersed and non-dispersed FARP operations. Figure 4-3 shows the distributions of the fuel consumption of the helicopters in both cases. A two-sample t-test (confidence interval 0.95) found a significant difference between helicopter fuel consumption in dispersed FARP operations (μ = 6420.29, σ = 246.85) and the helicopter fuel consumption in non-dispersed FARP operations (μ = 6184.79, σ = 300.76); t(6498) = -30.74, $p < 0.001$.

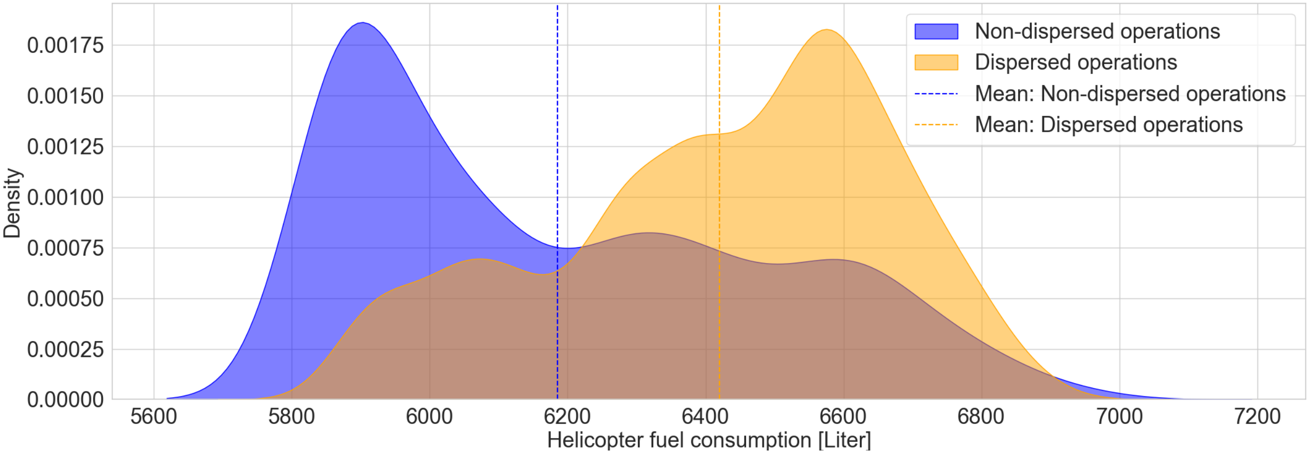


Figure 4-3: Distributions of helicopter fuel consumption in dispersed FARP operations and non-dispersed FARP operations.

5.0 DISCUSSION AND CONCLUDING REMARKS

The objective of this paper was to answer the research question: *"To what extent can simulation support the decision-making process of FARP operations?"* FARPs are important tools to extend the influence sphere of helicopters. However, because FARPs are planned on a per-mission basis, they have to be planned and deployed during the helicopter mission itself. Therefore, we investigated the use of M&S to support the decision-making process of FARP mission planners.

As FARPs have received little attention in the scientific literature, it was necessary to first create a model representing the factors that define a successful FARP operation. This model was informed by the few available scientific sources as well as exercise reports available online. From this model a set of key factors were selected to form a starting point for the simulation framework developed in this paper. These key factors focussed on helicopter fuel-usage, and thus the refuelling function of FARPs.

A simulation framework was developed that covers two aspects of FARPs: (1) the placement of the FARP in a mission area, and (2) the function of the FARP to extend the range of the helicopters. A simple geographical analysis was implemented to identify FARP locations on western European terrain. Monte Carlo simulation was used to approximate the probability of trucks reaching and setting up the FARPs on selected locations. A discrete event simulation was used to simulate the flight of helicopters between the FOB, the AOO and the FARPs.

The simulation framework was tested in two decision support use cases presented from a FARP mission planner's perspective. In the first use case, the FARP mission planner investigates the trade-off between helicopter fuel consumption and FARP survivability. The expected simple trade-off was found to be more complex in practice, but the simulation correctly showed how FARPs far away from the optimal flight path presented more danger to the trucks and also required a longer flight time (and thus more fuel) from the helicopters. A particular simulation artefact was observed in the results, but this artefact is expected to be resolved by the use of input data with a higher resolution. In the second use case, the FARP mission planner investigated the impact of dispersed and non-dispersed FARP operations on helicopter fuel consumption. The simulation showed a significant difference in fuel consumption. Although the simulation framework was applied to a single mission in this paper, it can likely be scaled up to also inform decisions regarding an entire operation's fuel supply chain.

In terms of future work, we identified a number of opportunities to improve the simulation framework for decision support purposes. By adding elements such as ammunition, human factors, different helicopter and mission types, the simulation framework can potentially be applied to identify more complex relations in and around FARP operations. Also, more realistic mission environments can be created by adding elements such as threat and risk factors. Furthermore, so far the FOB and AOO locations have been statically placed on the map. For example, adding no-fly zones will force the simulation to calculate alternative options which might better reflect a real-world scenario. However, operational application of the simulation framework as presented in this paper greatly depends on availability of realistic and up-to-date input data. For example, a concrete avenue for future work would be to replace the basic location analysis by a real-world GIS application (as mentioned in section 3.3) as well as looking into the integration of realistic flight models for helicopters.

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