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DISCRETE EVENT SIMULATION OF AIRCRAFT SORTIE GENERATION ON AN AIRCRAFT CARRIER

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ABSTRACT

The Sortie Generation Rate (SGR) which refers to the number of sorties that can be generated per unit time, is a key indicator for evaluating the ability of an airbase. However, an aircraft carrier has many constraints compared to a land-based airbase, such as spatial and environmental constraints, making it difficult to apply existing land-based research to analyze aircraft carrier operations. On the other hand, the Sortie Generation Process (SGP) on an aircraft carrier is similar to a logistics/production system in that sorties are generated through aircraft. Therefore, this study proposes a framework for analyzing the SGP on an aircraft carrier using discrete event simulation and defines the classes that make up the simulation. In addition, SGP analysis simulations were implemented using the proposed framework and several experiments were performed to demonstrate the feasibility of applying the proposed framework in practice.

1 INTRODUCTION

An aircraft carrier, which is a naval airbase, is a complex system that involves various components such as facilities, personnel, and aircraft that interact with each other (Lee and Park 2015). In addition, due to its sensitivity to external factors such as operational and tactical situations, the behavior of an aircraft carrier is complex and unpredictable. Since having perfect information about the behavior of the components and external environment of an aircraft carrier is practically impossible, modeling with an appropriate level of abstraction is important for system analysis of an aircraft carrier.

The Sortie Generation Process (SGP) refers to a series of processes necessary for generating aircraft sorties. It focuses on major events such as the beginning and end of various tasks and the occurrence of failures, while considering the complex behavior and kinetics of various components and environmental factors only indirectly as stochastic factors. Therefore, the SGP is a stochastic process with probabilistic changes over time. The first order moment based on the mean of processing time provides important intuition for understanding the behavior of stochastic processes (Hopp and Spearman 2011). The Sortie Generation Rate (SGR), which represents the number of sorties generated per unit time, is one of the first-order moments related to the SGP and serves as a benchmark for creating Air Tasking Orders (ATO) and planning operations. Therefore, analyzing the SGP can be considered as calculating the SGR.

In general, aircraft require runways of at least 1.8km and various support facilities and equipment for takeoff and landing. However, even the largest existing aircraft carrier, the USS Gerald R.Ford (CVN-78), is only 333m long. This aspect places aircraft carriers in the category of small-scale airbases having significant spatial constraints compared to ground bases. The spatial constraints of an aircraft carrier pose additional challenges to modeling. Due to limited space, factors such as crew rest and limited operation time need to be carefully considered. With only one runway available, the sequencing of launches and recoveries becomes crucial. The internal hangar location necessitates the use of lifts for movement between the deck and hangar for maintenance purposes. However, the limited number of lifts, dictated by the carrier's structure, further complicates the modeling process. As a result, aircraft carriers have a significantly different SGP than the typical SGP of ground bases due to their spatial limitations. Therefore, modeling methods for analyzing the SGP of aircraft carriers need to be different from those used for ground bases.

Previous research on SGP has mainly used simulation and analytical methods. Boyle (1990) performed research on the interaction of SGP considering the influence of logistics and personnel using the Logistics Composite Model (LCOM). Dietz and Jenkins (1997) and Hackman and Dietz (1997) proposed a mathematical model based on Mean Value Analysis (MVA) for SGP analysis. Harris (2002) developed an SGP analysis model that could support the decision-making of air commanders. Faas (2003) and Bingol (2016) analyzed the impact of the Autonomic Logistics System (ALS) on SGP through simulation. Aykiri (2016) analyzed the influence of personnel and various resources on SGP and bottleneck processes through simulation. However, most previous works focus on ground bases and do not take spatial constraints into account. Therefore, the application of those studies' analysis of aircraft carrier SGP is limited. The goal of this study is to conduct SGP analysis that considers spatial constraints, aiming to address the limitations of previous studies that have predominantly focused on ground bases and neglected such consideration.

Table 1: Related works for SGP.

Author (year)	**Target**	**Methodology**	**Reflects flight schedule**	**Stochastic approach**	**Spatial constraints**
Boyle (1990)	Ground bases	Simulation	No	No	No
Dietz and Jenkins (1997)	Ground bases	Mathematical	No	No	No
Hackman and Dietz (1997)	Ground bases	Mathematical	No	No	No
Harris (2002)	Ground bases	Simulation	Yes	No	No
Faas (2003)	Ground bases	Simulation	Yes	Yes	No
Bingol (2016)	Ground bases	Simulation	Yes	Yes	No
Aykiri (2016)	Ground bases	Simulation	Yes	Yes	No
This study	Aircraft carriers	Simulation	Yes	Yes	Yes

In the SGP system, aircraft go through processes such as weapon loading and refueling to generate sorties. Each process shas its designated location, and once the aircraft completes a process at a specific location, it moves to a different location for the next process. In logistics/production systems, raw materials or intermediate parts go through multiple operations to produce the final product. Each process takes place in a designated workspace, and once the operation is completed, the parts move to the next workspace. In this aspect, the SGP system is similar to logistics/production systems, where aircrafts correspond to parts, each process in the SGP corresponds to an operation, the locations where processes occur in an aircraft carrier correspond to workstations, and sorties correspond to final products. There are many studies using Discrete Event Simulation (DES) in the field of logistics/production. Woo et al. (2017) proposed a simulation framework for supply chain management. They introduced a 6-Factor information structure for simulation and defined the simulation's targets and Key Performance Indicators (KPIs). Woo et al. (2010) and Jeong et al. (2018) performed analysis on logistics systems using process-centric discrete event simulation. Since production systems have interconnected processes and parallel resources within each process, previous research on logistics/production systems using process-centric discrete event simulation provided valuable insights for this study. However, while a typical logistics/production system is an open system with the creation and elimination of parts, the SGP system is a closed system where a predetermined number of aircraft continuously circulate within the SGP, generating sorties. This poses limitations in applying previous research to aircraft carriers.

In this study, we implemented the process of generating sorties through a series of SGP using discrete event simulation of an aircraft carrier. In Section 2, the methodology and framework used to develop the simulation will be introduced and in Section 3, the implementation of the model will be described in detail. In Section 4, the results of the case study, which involved varying the number of aircraft and the layout of the aircraft carrier, will be presented.

2 METHODOLOGY

2.1 Graph Modeling

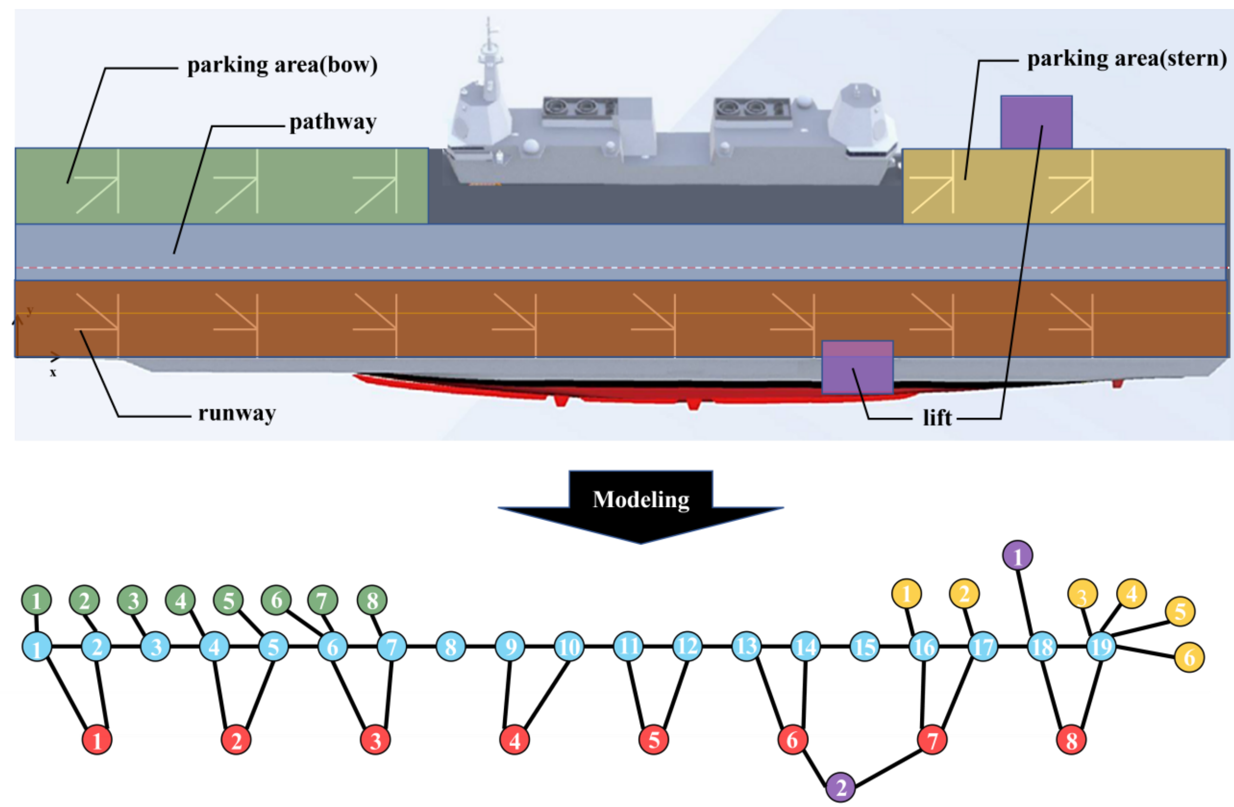

Figure 1: Example of graph modeling.

In analyzing SGP on an aircraft carrier, it is important to reflect the spatial elements of the carrier as it has relatively limited space compared to ground bases. In particular, the interference between aircraft when moving on the deck creates significant constraints on generating sorties from the deck. Therefore, it is important to simulate the movement of aircraft on the deck. However, considering the interference between aircraft in a continuous space within discrete event simulation can be computationally time-consuming. Additionally, due to the stochastic nature of the simulation, iterative calculations are necessary, making it essential to reduce the computation time in SGP simulations. Therefore, from a computational standpoint, considering continuous space on the deck is practically difficult. As a result, a separate logic is required to implement the movement of aircraft on the deck.

In this study, the deck of an aircraft carrier is modeled as a graph structure, as shown in Figure 1. The major points of the aircraft carrier are created as nodes, and the nodes are connected by an edge to form a disjunctive graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$. Here, $\mathcal{V}$ represents the set of nodes, and $\mathcal{E}$ represents the set of edges.

$$\mathcal{V} = \{v_i | i = 1, \dots, N\}$$
$$\mathcal{E} = \{e_{i,j} = (v_i, v_j) \,|\, v_i \text{ is linked to } v_j, \forall v_i, v_j \in \mathcal{V}\}$$

Afterwards, the connectivity and distance between each node are represented by the symmetric matrices, adjacency matrix and weight matrix, respectively. Each matrix can be defined as follows, where $w_{i,j}$ represents the distance between v_i and v_j.

$$A[i,j] = \begin{cases} 1, & if\ v_i\ is\ linked\ to\ v_j \\ 0, & otherwise \end{cases}$$
$$W[i,j] = \begin{cases} w_{i,j}, & if\ v_i\ is\ linked\ to\ v_j \\ 0, & otherwise \end{cases}$$

In Figure 1, the deck of the aircraft carrier is divided into five sections: parking area (bow), parking area (stern), pathway, runway, and lift. Generally, activities such as weapon loading and refueling take place in the parking area section, while fully prepared aircraft move through the pathway to the runway to launch. Additionally, aircraft requiring maintenance need to descend from the deck to the hangar, using the lift. Each section, divided according to its purpose, is represented using an appropriate number of nodes. The number and placement of nodes are determined considering the size and shape of the aircraft carrier and aircraft. Having more nodes and a denser distribution allows for more precise consideration of movement on the deck, but it also increases the computational complexity. The pathway, which encompasses the movement from the parking area to the runway, requires a more detailed representation to account for the aircraft's movement, thus having highest number of nodes in Figure 1.

2.2 Simulation Framework

Figure 2 shows a simulation framework customized for the sortie generation process simulation based on the simulation framework proposed by Nam et al. (2022). The simulation framework consists of five componenets: ① Adapter component, ② Simulation component, ③ Modeler component, ④ Data component, ⑤ Reporter component. A brief description of the role of each component is as follows.

- ① Adapter component: Processes user input such as FlyPro and SGP to make it readable by the simulation.
- ② Simulation component: A set of classes that implement the main elements of the sortie generation process simulation, including fighter, process, location, etc.
- ③ Modeler component: Utilizes the Adapter component to process the data and Simulation component's classes to model the SGP.
- ④ Data component: Determines the next action a_t of the simulation at the state s_t of the simulation model according to the predetermined operation policy.
- ⑤ Reporter component: Processes the event log generated by the simulation into the desired information format by the user.

Using the data processed in component ① and the classes in component ②, the model is implemented in component ③. Component ③ interacts with component ④ by passing the state s_t of the model at timestep t which determines the next action a_t of the simulation according to the predetermined operation policy. In component ③, events are generated based on the received action a_t, which are then passed to the DES engine to obtain the state at the next timestep, s_{t+1}, and this process is repeated. Once all events are completed, an event log containing all simulation results is generated and passed to component ⑤ for processing into the desired output format for the user.

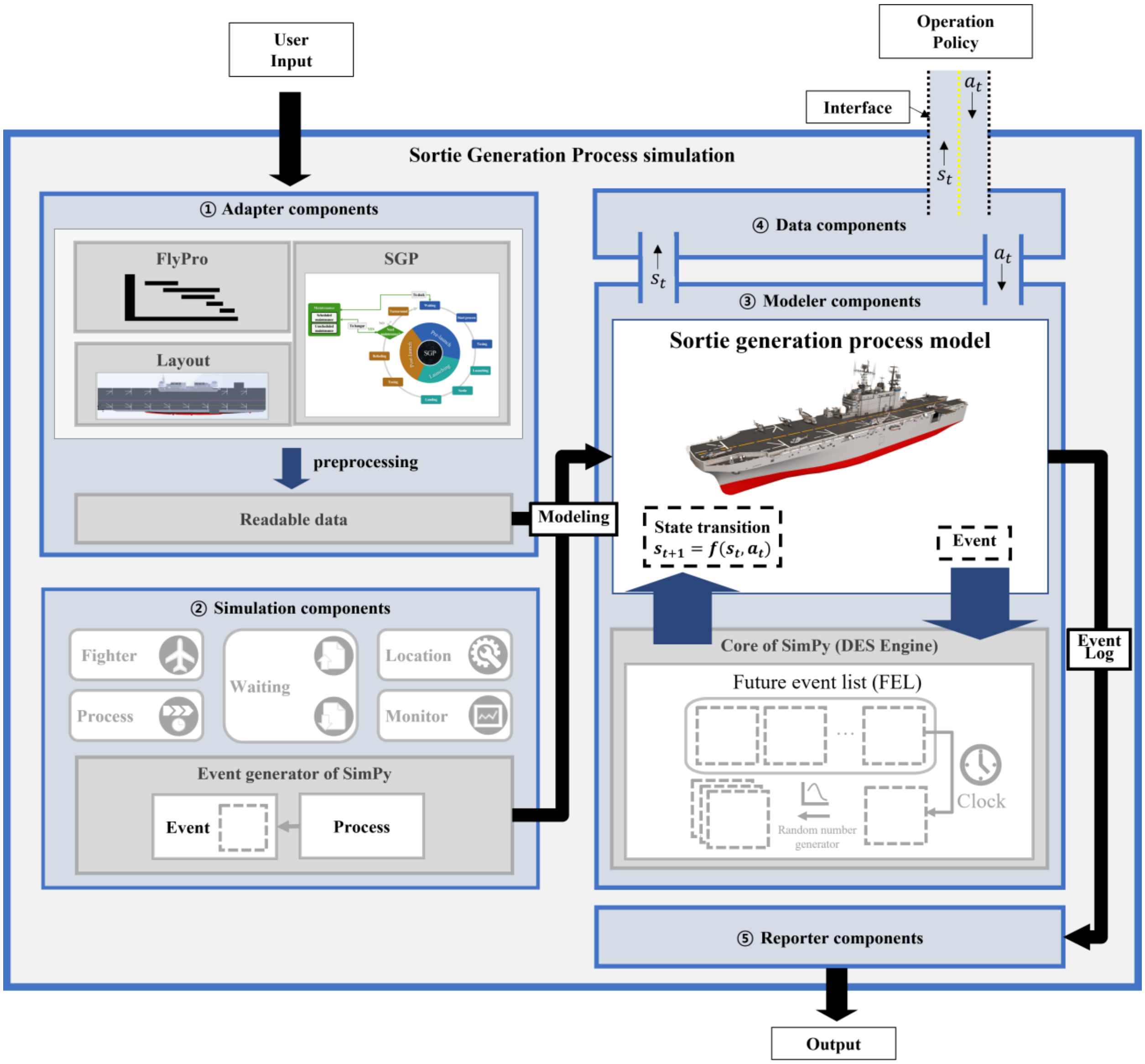

Figure 2: Framework for SGP simulation.

3 MODELING

To model the simulation using the framework presented in the previous section, it is necessary to define the input data and design the simulation components. In this study, the input data is defined as SGP, FlyPro and layout. The simulation components were implemented using SimPy, an open-source DES package based on Python.

3.1 Input Data

The input data for the simulation includes information on the service time and spatial information for each process of the SGP, FlyPro for flight schedules, and information on the layout of the aircraft carrier. The SGP on the aircraft carrier is typically organized as shown in Figure 3, divided into pre-launch and post-launch phases based on launching and landing. The detailed processes for each phase can vary depending on the type of mission. Therefore, various SGPs can be customized and experimented with by adding or removing processes, among other modifications. The SGP includes information on the distribution of service time for each process and the locations where they can be performed. The SGP created as described above is used to create the flight schedule.

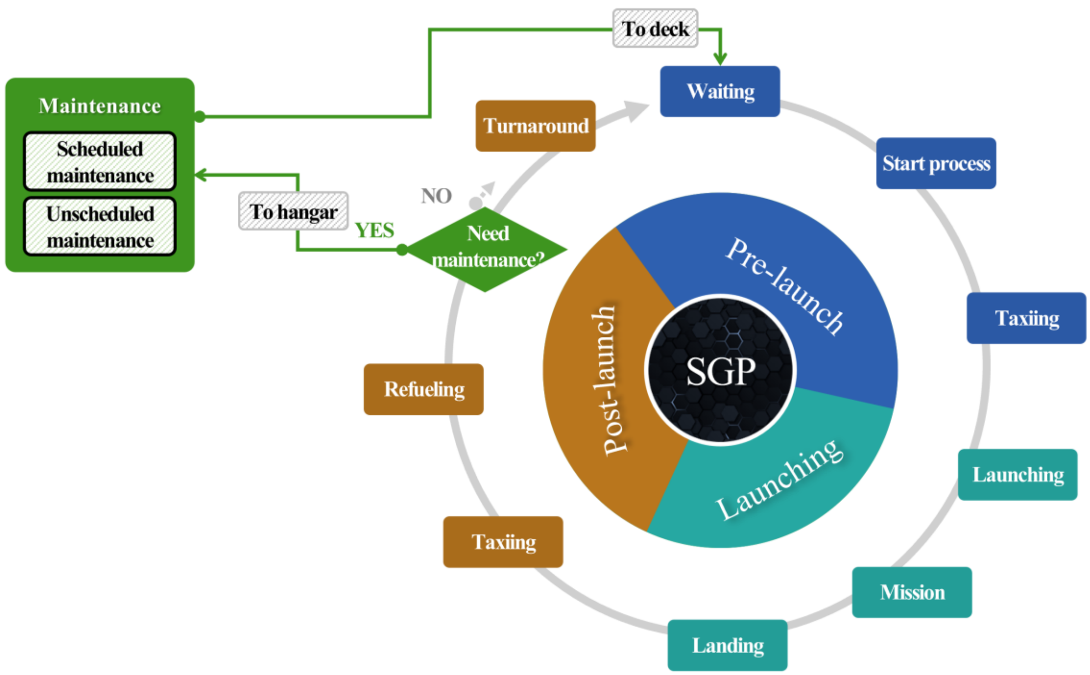

Figure 3: Example of SGP data.

The flight schedule is managed as input data in the form of a chart called FlyPro. FlyPro includes information such as the type of aircraft required for each mission, the number of aircraft in the formation, the start time and duration of the mission, and the type of SGP required for the mission. The simulation references the chart to trigger the start of SGP and selects the appropriate aircraft for the mission. Additionally, each mission includes a cancellation threshold to implement the operation policy for canceling missions if they are delayed for a certain period of time.

Information about the layout of the aircraft carrier is provided by the graph modeling introduced in Section 2, which includes an adjacency matrix representing the connection relationships between each node and a weight matrix representing the distance between them. Using these matrices, the shortest path matrix $S[i,j]$ and the distance matrix $D[i,j]$ for each path are generated. These matrices are referenced when the aircraft moves between each node.

3.2 Simulation Components

In this study, the SGP occurring on an aircraft carrier is mapped onto a logistics/production system and implemented using five classes: fighter, processing, location, and monitor, with the source and sink integrated into the waiting class. Each class represents a component of the simulation. These 5 classes are explained in further detail in Sections 3.2.1 - 3.2.5.

3.2.1 Fighter Class

Fighter class models the aircraft and includes their characteristics such as ID, type, current location, mission plan, and accumulated flight count, as well as their state information such as “available”, “unavailable”, and “in operation” as they pass through multiple process objects. The fighter’s state changes repeatedly among these statuses throughout the simulation.

3.2.2 Process Class

Process class is a class that implements the unit processes that make up the model. Process class generates time progression through timeout events. SimPy’s store is used to implement the movement of fighters. When a fighter object completes its task within a process object, it is passed on the next process object’s store, based on the fighter’s status information. If the next process can be carried out at the fighter’s current location, it proceeds immediately, otherwise the fighter is moved to a possible location. To achieve this, the shortest path matrix and distance matrix are referenced, and the process of occupying the path that needs to be passed to move to the target location, waiting for the movement time, and releasing occupation is repeated to move the fighter between nodes. Furthermore, the movement of the fighter is calculated considering two types of movements: the cold move which refers to moving the fighter using a tractor while the engine is turned off, and the hot move which refers to moving the fighter using its own power while the engine is on. The travel time is calculated based on the speed of each type of movement when the fighter is being moved.

In this study, specific processes were inherited from the base process class and modified to reflect various constraints on aircraft carriers. A typical example includes launching and landing. To begin these processes, all assigned fighters in the squadron must be ready and all runways must be clear. Additionally, after landing, the number of fighter takeoffs must be updated, and maintenance needs must be checked. These constraints cannot be simply reflected through a timeout, so a separate class was created by inheriting from the process class to implement them.

3.2.3 Waiting Class

In general logistics/production systems, there are usually open systems with sources that generate parts and sinks that dispose of them. However, in the case of the SGP system on an aircraft carrier, it is a closed system where a fixed number of aircraft repeatedly participate in the SGP process to generate sorties, rather than being created and disposed. Therefore, the roles of source and sink are combined in the waiting class, which manages flight schedules. When a mission preparation time is reached, the waiting class assigns the appropriate SGP to the available fighter objects. Furthermore, fighter objects that have completed assigned SGP enter the waiting class again, indicating that the aircraft is available for use.

3.2.4 Location Class

The layout of the aircraft carrier is modeled as a disjunctive graph, as shown in Figure 1. Each node of the graph is used as a resource to implement spatial constraints on the carrier deck. To reflect the spatial occupancy from the operational perspective of the aircraft carrier, the model considers the conditions that both the pathway and runway must be clear when the aircraft launches, and that the lift on port side cannot be used within a certain time frame due to the use of the runway. Furthermore, in terms of the occupation of the runway, priority is given to the launching over the recovering, as maximizing the deck space for the aircraft is important. Therefore, the launch process is given a higher priority for the occupation of the runway than the recovery process.

3.2.5 Monitor Class

As each fighter passes through each process, various events occur. The monitor class records and manages information about these events. After the simulation is complete, the stored information is output in log format. Each event represents the start and end of a process and moving, and the log includes information about the aircraft involved in the event and the location where the event takes place.

4 CASE STUDY

4.1 Problem Definition

The factors that affect the success rate of sortie generation for fighters can be broadly categorized into the number of fighters, the layout of the aircraft carrier, the service time of each process, and the tightness of FlyPro, which represents the intervals between each mission. In this study, 8 experiments are performed by varying the number of fighters and the layout of the aircraft carrier. The conditions for each experiment are shown in Table 2, and it is assumed that there is one Search and Rescue (SAR) helicopter in all cases.

Table 2: Summary of experiments.

Case	Capacity of parking area	Detailed case	Number of fighters
Case 1	Bow: 7 Stern: 5	Case 1-1	16
		Case 1-2	20
Case 2	Bow: 8 Stern: 6	Case 2-1	16
		Case 2-2	20
Case 3	Bow: 9 Stern: 7	Case 3-1	16
		Case 3-2	20
Case 4	Bow: 10 Stern: 8	Case 4-1	16
		Case 4-2	20

Table 3: SGP data for experiments.

Type of fighter	Process	Distribution	Parameters (min)	Location
Fighter	Start process	Triangular	30, 40, 50	Parking area
	Launching	Uniform	1, 2	Runway
	Landing	Uniform	0.5, 1	Runway
	Refueling	Triangular	30, 40, 50	Parking area
	Weapon unloading	Uniform	20, 30	Parking area or runway
	Maintenance	Deterministic	120	Hangar
SAR helicopter	Launching	Uniform	4.5, 5.5	Front node of runway
	Landing	Uniform	4.5, 5.5	Front node of runway
	Refueling	Triangular	15, 20, 25	Front node of runway
Common	Lift down/up	Deterministic	1	Lift
	Lashing	Deterministic	3	Parking area or lift
	Unlashing	Deterministic	3	Parking area or lift

The SGP used in the experiment is shown in Table 3, and the same SGP is applied to all aircraft except for SAR. There are two cases in which an aircraft enters the hangar during SGP. The first case is when there is no available parking area after completing the mission and landing on the deck. In this case, the aircraft moves to a designated temporary location on the runway, completes the weapon unloading process shown in Table 3. The second case is when the aircraft needs planned maintenance. In this experiment, only scheduled maintenance is considered, and it is assumed to be performed after two sorties. In this case as well, the aircraft completes the weapon unloading process on the deck and then goes down to the hangar. FlyPro corresponding to two days of flight plan was used in the experiment using this kind of SGP. All missions required 60 minutes, consisted of four aircraft in a formation, and were scheduled every 100 minutes. In addition, SAR also had a 70-minute mission scheduled every 100 minutes for a total of eight times a day.

If a delay of more than 20 minutes occurs for any scheduled mission, the mission is canceled, and the assigned aircraft are returned to the available state. In this case, the canceled mission is considered a mission failure, while missions that proceed with delays within 20 minutes are considered mission successes. In this study, the mission success rate is set as the key performance indicator (KPI), and the results were analyzed through experimentation as defined earlier.

4.2 Results

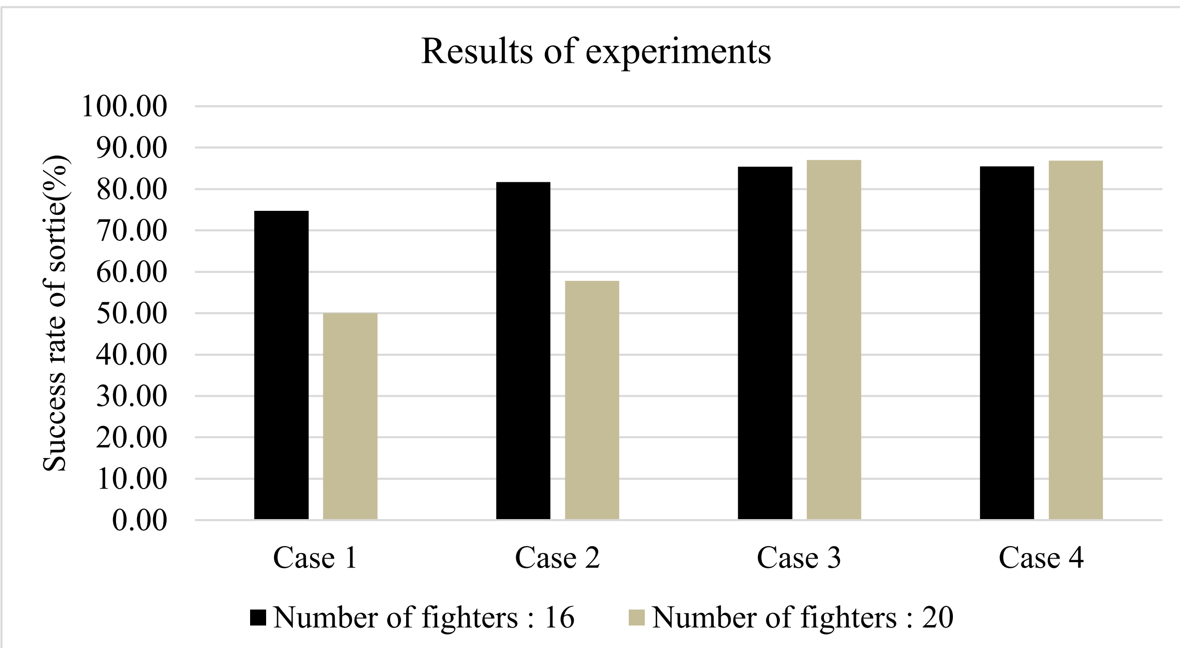

Figure 4: Results of experiments.

Table 4: Statistical significance of the results.

Case	Detailed case	The average Success rate of sortie (%)	Confidence interval (%)
Case 1	Case 1-1	74.7	74.5-74.9
	Case 1-2	50.0	50.0-50.0
Case 2	Case 2-1	81.7	80.6-82.8
	Case 2-2	57.8	56.0-59.6
Case 3	Case 3-1	85.4	84.8-86.1
	Case 3-2	87.0	86.7-87.3
Case 4	Case 4-1	85.5	84.8-86.1
	Case 4-2	86.8	86.5-87.2

. Table 4: Statistical significance of the results

The experiments for each case are repeated 1,000 times, and Figure 4 shows the average sortie success rate for each case. Table 4 shows the averatge sortie success rate for each case along with the confidence intervals at a 95% confidence level. In general, it can be observed that the higher the capacity of the aircraft carrier and the number of fighters, the higher the sortie success rate for the corresponding FlyPro. In Case 1 and Case 2, the success rate is higher when the number of aircraft is 16 compared to 20. However, in Case 3 and Case 4, the success rate is higher when the number of aircraft is 20. In this study, the operational approach of maximizing the utilization of the deck was chosen. Therefore, in smaller aircraft carriers such as Case 1 and Case 2, congestion occurred, and increasing the number of aircraft had a negative impact on success rate. Therefore, it can be concluded that increasing the number of deployed aircraft from 16 to 20 in small aircraft carriers like Case 3 and 4 is a good decision, while it is not good decision in larger aircraft carriers like Case 1 and 2. These simulation results can not only be used to determine the number of deployed aircraft but also to design the layout of the aircraft. To achieve a sortie success rate of over 80% for a given FlyPro, it is essential to design the layout of the aircraft carrier with a capacity of Case 2 or higher.

This simulation is conducted on an 11th Gen Intel® Core i7- 11700 CPU with RAM 16GB, and it took approximately 247 seconds to run one case 1,000 times. This translates to approximately 0.247 seconds per run, which is a reasonable time for both military personnel who need to plan flight operations and designers who need to test various designs.

5 CONCLUSION

In this study, a discrete-event simulation framework is proposed for analyzing the Sortie Generation Process (SGP) of an aircraft carrier based on the SimPy package. Using the proposed framework, simulation is implemented, and experiments is conducted on 8 different cases. The experimental results revealed variations in sortie success rates depending on the size of the aircraft carrier and the number of aircraft. Additionally, by taking the layout of the aircraft carrier as input data, our framework can help designers to make more appropriate layouts by referring to the quantitative results of the simulation. Similarly, by taking the SGP and FlyPro as input data, various experiments can be conducted on the flight plan and operational policy of the aircraft carrier, providing valuable insights to actual operators.

However, the Reporter class in Figure 2 has not yet been implemented and experimented on. In future work, if it is implemented, it will help facilitate a more intuitive understanding of the experimental results and allow for a more in-depth analysis of the specific causes of sortie generation failures, thus leading to a deeper understanding of the SGP process. Furthermore, in this study, a deck operation policy is implemented aimed at maximizing deck utilization. In addition to this, it would be meaningful to explore various deck operation policies to find the optimal one for different scenarios.

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