International Journal of Organizational Innovation

SYSTEM DYNAMICS ANALYSIS OF FLIGHT SIMULATOR MAINTENANCE AND PARTS INVENTORY MANAGEMENT

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Abstract

Flight simulators are commonly used to train pilots. In response to external military threats, the Taiwanese government has prioritized training fighter pilots and devoted high-end training aircrafts and flight simulators to increase the safety and quality of pilot training. The frequency of flight simulator malfunction increases with use and time, and the diminishing number of part suppliers exacerbates the difficulty of maintenance, which affects pilot training. We use system dynamics to develop a model of maintenance and parts inventory management for high-end simulators. The model is also used to explore the effects of various policies on simulator reliability and maintenance cost. The managerial implications of the results are also presented.

Keywords: system dynamics, flight simulator, inventory management, maintenance cost

Introduction

Taiwan is situated in a critical military position in the Asia Pacific region. In response to powerful military threats, fighter pilots must undergo flight training to maintain aerial superiority. Despite the considerable funding for flight training, safety concerns remain for fighter pilots. Taiwan's limited number of flight training bases is insufficient to meet the demands of the military and private airline companies. As a result, flight training for fighter pilots relies on advanced, realistic flight simulators. Dynamic flight simulators behave similarly to real aircrafts and enable training at any time, ensuring pilots can train safely and consistently during their courses and thus increasing flight safety and reducing training costs.

The Taiwanese government has prioritized the training of fighter pilots and devoted high-end training aircrafts and flight simulators to increase the safety and quality of pilot training. Taiwan's high-end training aircrafts and flight simulators have been used for several years. With advancements in technology, differences between the newer digital flight simulators and older simulators have emerged, resulting in compatibility problems. Because the efficiency and effectiveness of old flight simulators do not meet commercial standards, the number of suppliers has decreased. In addition, old flight simulators frequently malfunction, and the number of suppliers of key parts has decreased, making maintenance difficult and in turn affecting the outcome of pilot training (Jan and Hsiao, 2004).

Flight simulators consist of military-grade parts that often have no suppliers in Taiwan and are thus imported from other countries. This increases the time and cost required to procure the parts, and the disappearance of suppliers has complicated inventory management (Livingston, 2000; Patrick, 2019). Because simulator maintenance and parts inventory management involve numerous factors, this study applies system dynamics theory to analyze the high-end AT-3 flight simulator, the most commonly used simulator in the Taiwanese air force, and develop a maintenance and parts inventory management model. This study also explores the effects of regulations on operation time and inventory management on the availability and maintenance cost of simulators and describes managerial implications.

Literature Review

Simulation training is a teaching method that combines embedded functions and realistic content to create a practical learning experience (Cannon-Bowers and Bowers, 2009). Simulation equipment are used to create a highly realistic virtual environment for training courses (Issenberg et al., 2005). Simulators have been widely used in professional training to cultivate talent, the medical field to train surgeons and nurses, the engineering field to provide training for operating heavy-duty machinery in logging, piloting, and rail transport, and the military to simulate tanks, naval ships, submarines, and fighter aircrafts (Jha et al., 2001; Kreisher, 2006; Ranta, 2009). Simulators familiarize trainees with machines, reduce the risk of error (Neukum et al., 2003), and provide a safe environment for trainees to practice in uncommon scenarios without the limitations of external factors (e.g., weather and location). Because the environmental conditions of a simulation can be controlled, the training process can be standardized, and the cost can be reduced (Diedrich, 2006), thus creating a flexible, safe, and consistent learning environment (Ranta, 2009).

With the exception of countries with advanced fighter and training aircrafts, most countries have used fighter aircrafts and flight simulators for some time. Simulator maintenance is complicated by diminishing manufacturing sources and material shortages (DMSMS). DMSMS occurs when manufacturers stop producing a specific part, resulting in procurement problems and directly affecting simulator maintenance (Patrick, 2019). DMSMS can be resolved by devising responsive measures during the product design and system development stages (Livingston, 2000). If users of a product adopt a passive management approach toward DMSMS, they may incur considerable costs and encounter complications that prevent tasks from being completed. Responsive measures to DMSMS include analyzing part suppliers, finding substitutes, preparing materials, redesigning products, and adjusting operating systems.

Flight simulator maintenance and parts inventory management are dynamic and complicated processes. Studies have proposed the use of systems thinking to analyze these processes (Sterman, 2000). System dynamics (SD) is based on using feedback to control a system and solve dynamic and complex problems encountered by corporations and social organizations from a comprehensive perspective. SD prevents the fragmentation of thinking caused by myopic viewpoints and involves modeling a particular topic by controlling variables through computer simulation and identifying solutions on the basis of the results (Forrester, 1961).

The causal feedback loop used in SD can be used to solve problems in complex, dynamic systems involving reciprocal causation (Zhao et al., 2015). SD also involves using fluid dynamics to represent the parts, materials, maintenance, and human resources of a system as dynamic flows. In addition, SD accounts for the rate and stock of variables and can be used to determine the value of control and state variables in decision-making. Therefore, SD can be used to analyze the dynamic processes of policy- and decision-making, and it has been widely applied to research on military aircraft, vessel, and helicopter maintenance (Jones et al., 2010). From a macroscopic perspective, simulator maintenance involves numerous variables, including operations, maintenance, part substitution, and inventory management. Because these variables affect each other dynamically, this study employs SD to develop a model and analyze policy-making.

Model Development

SD models consists of arrows that represent the causal links, level, rate, and auxiliary of information feedback (Forrester, 1961). Figure 1 presents the symbols and flow chart used in SD

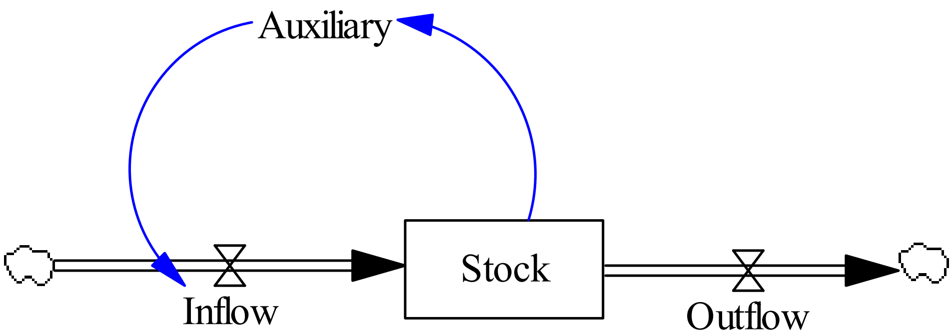

Figure 1. Symbols and Flow Chart Used in SD

The stock coefficient represents a system's total output at a given time, represented by (1).

$$\text{Stock}(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]ds + Stock\,(t_0) \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

Inflow(s) is the inflow of a system, Outflow(s) is the outflow of a system, and Stock(t_0) is the initial stock of a system. The stock coefficient for time t is the total net flow of each time interval added to the initial stock. Rate represents the control quantity of the inventory and is used to determine the stock accumulation speed. Auxiliary represents the relationship between inventory and rate. SD models can represent the causal relationship between variables in a system and the direction of link relationships. Visual models can be used as a recording structure to develop dynamic models and identify the structural properties of a system.

This study uses Vensim DSS to develop a model of simulator maintenance and parts inventory management by using key variables identified through a literature review and interviews with experts with practical experience. To increase the validity of the model, the simulator and maintenance components were analyzed to determine the fitness of each key variable in the causal relationships and ensure that the model accurately represented the simulator. The model consists of two sections: the simulator operations section and the equipment maintenance and parts inventory management section.

Simulator Operations

The Taiwanese air force uses the AT-3 flight simulator for basic flight training, advanced flight training, flight retraining, and simulator training. During simulator training, trainees must use the simulator every day to complete various combat readiness missions and tasks. The air force determines the duration of daily simulator practice. As the simulator is used, total operating time may exceed the mean time between failures (MTBF) of the system's key parts. This may result in malfunction and reduce the reliability of the simulator. When key parts malfunction, simulators must be shut down for maintenance and part replacement. After maintenance, training can be resumed. Increasing the reliability coefficient of the simulator increases the overall reliability. Figure 2 presents a model of simulator operations.

Equipment Maintenance and Parts Inventory Management

Simulator equipment maintenance involves repairable and unrepairable parts. Maintenance of repairable parts is economically expedient and performed on parts with moderate damage to restore function. However, maintenance of repairable parts creates is time consuming. Unrepairable parts require replacement. However, because of administrative procedures and factors related to delivery, part delivery may be delayed. The AT-3 flight simulator has been used for 20 years, but DMSMS has complicated the maintenance process. To ensure long-term simulator use, the military should develop policies to establish backup part

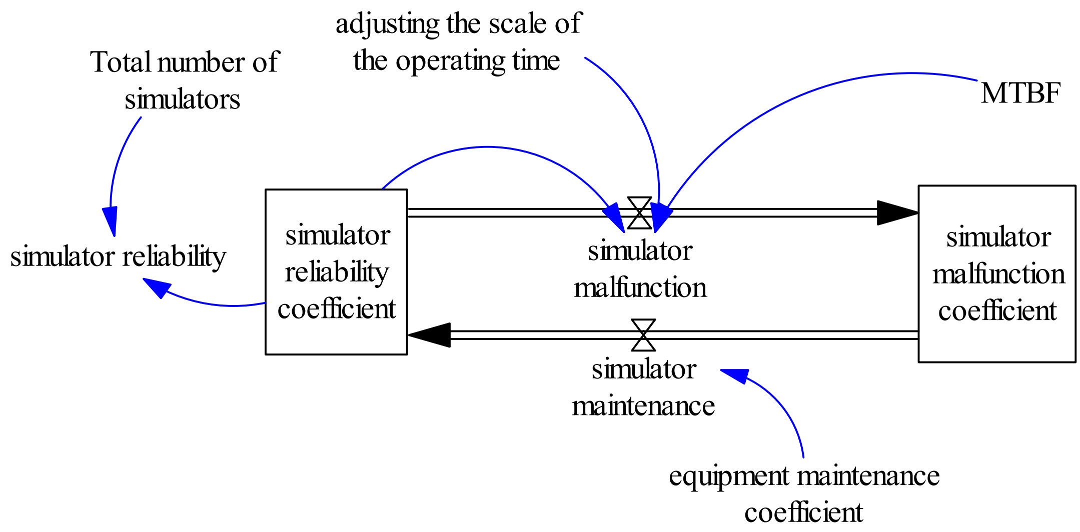

Figure 2. Simulator Operations

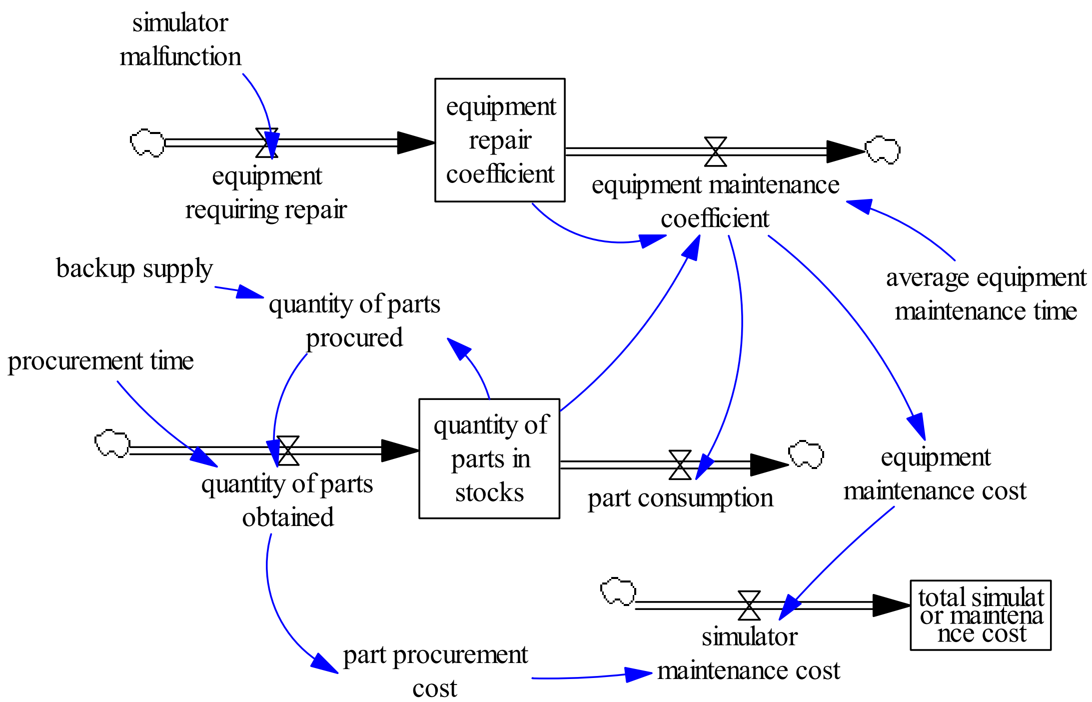

Figure 3. Model of Equipment Maintenance and Parts Inventory Management

supplies, thereby reducing the uncertainty caused by DMSMS and delays in part delivery. Because both the maintenance of repairable parts and procurement of unrepairable parts incur human engineering, administrative, and transportation costs, this study explores total maintenance cost under various policies by using cost-related terms. Figure 3 presents the model of simulator equipment maintenance and parts inventory management. Complete Model and Model Verification

The AT-3 flight simulator maintenance model represents the operations, equipment maintenance, and inventory management of the simulator (Figure 4). We referenced the methods proposed in Forrester and Senge (1980) and Sterman (2000) to test the model's structure and behavior and used Vensim DSS to determine its logical rationality. The results indicate that the model is adequately valid. To determine its accuracy, we performed a mean absolute percentage error (MAPE) analysis (Lewis, 1982) to compare the simulated and empirical values. As a relative value, MAPE is not affected by difference in units between simulated and empirical values. Therefore, the difference between simulated and empirical values can be determined objectively. Equation (2) is used to calculate MAPE.

$$\text{MAPE} = \frac{100}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \cdots\cdots\cdots\cdots\cdots (2)$$

A_t is the actual value, and F_t is the forecasted value. The MAPE of the inventory of heading devices, a key component of the simulator, is 6%, which indicates high prediction accuracy (Lewis, 1982). Therefore, the model was used to explore the effects of operating time and backup supply on reliability and total maintenance cost.

Simulation and Analysis

Variables affecting the use of the flight simulator were input to the model. Figure 5 depicts the simulated reliability of the simulator were the operating time and inventory management method to remain the same. The results indicate that the difficulty of procuring parts decreases reliability over time. If operating time and inventory management method were to remain the same, the decrease in simulator reliability would affect the process of flight training for the air force.

Simulation of Operating Time

Longer operating times result in lower MTBFs and shorter intervals between malfunctions, whereas shorter operating times result in higher MTBFs. Although shorter operating times reduce the frequency of malfunctions, the training process may be negatively affected. We used the model to explore the respective changes in reliability when operating time is increased and decreased by 10% (Figure 6). The results reveal that decreasing operating time results in long periods of favorable reliability, whereas increasing operating time increases the frequency of malfunction and decreases reliability considerably.

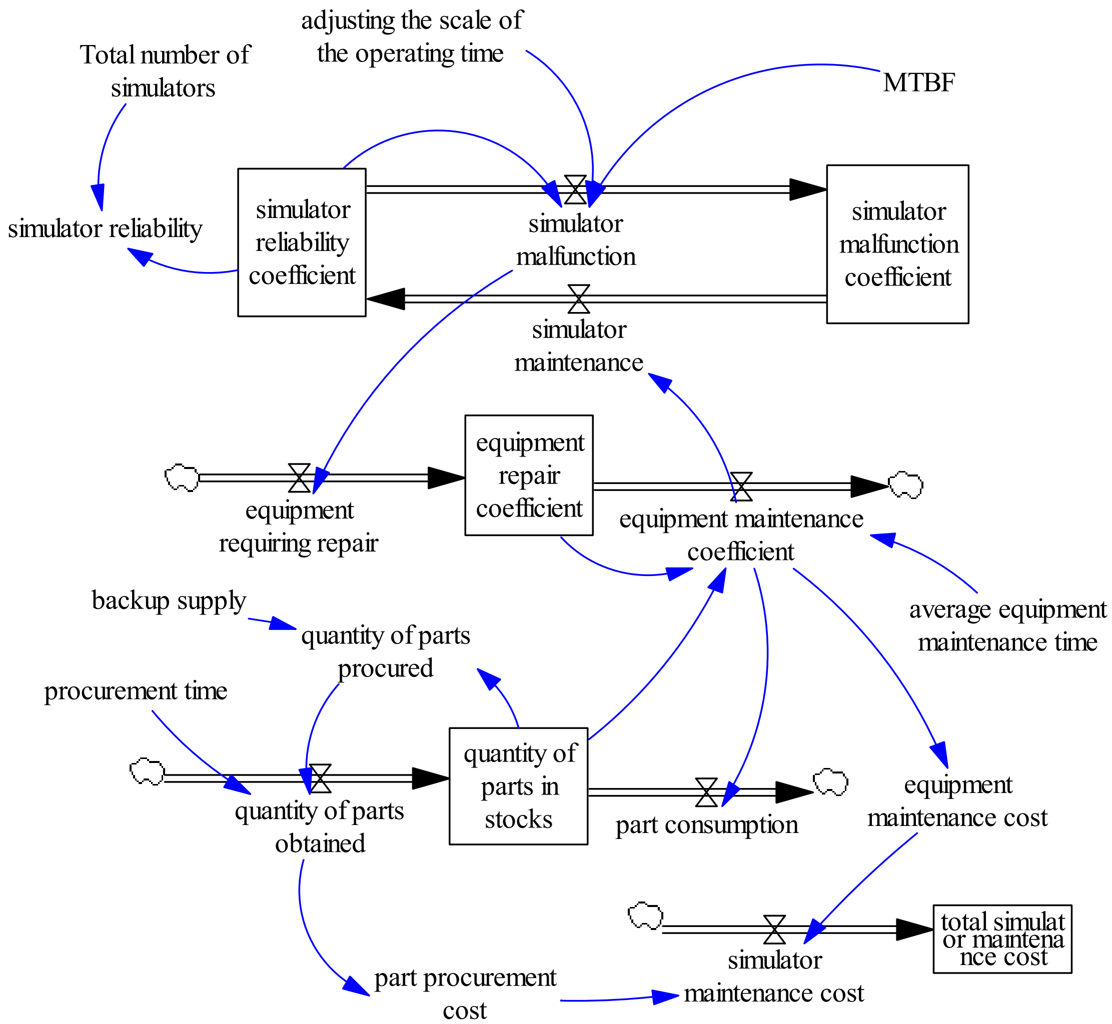

Figure 4. AT-3 Flight Simulator Maintenance Model

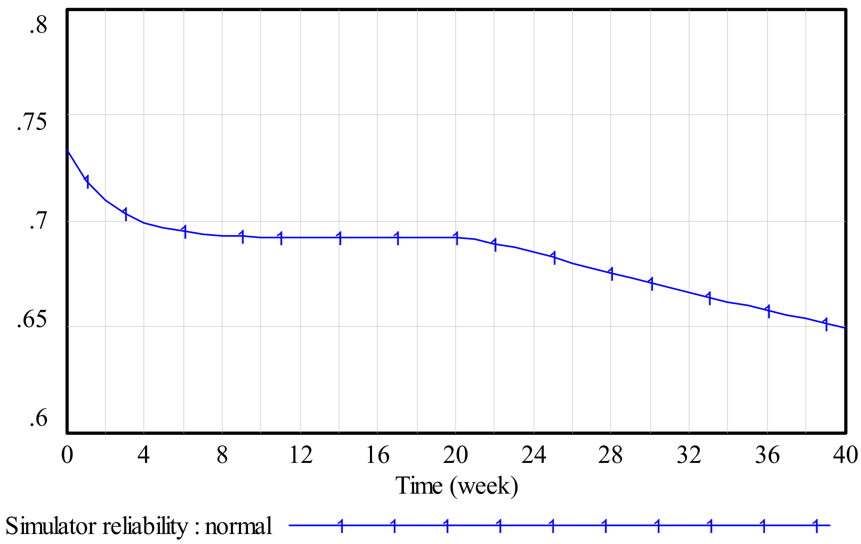

Figure 5. Simulated Simulator Reliability over Time

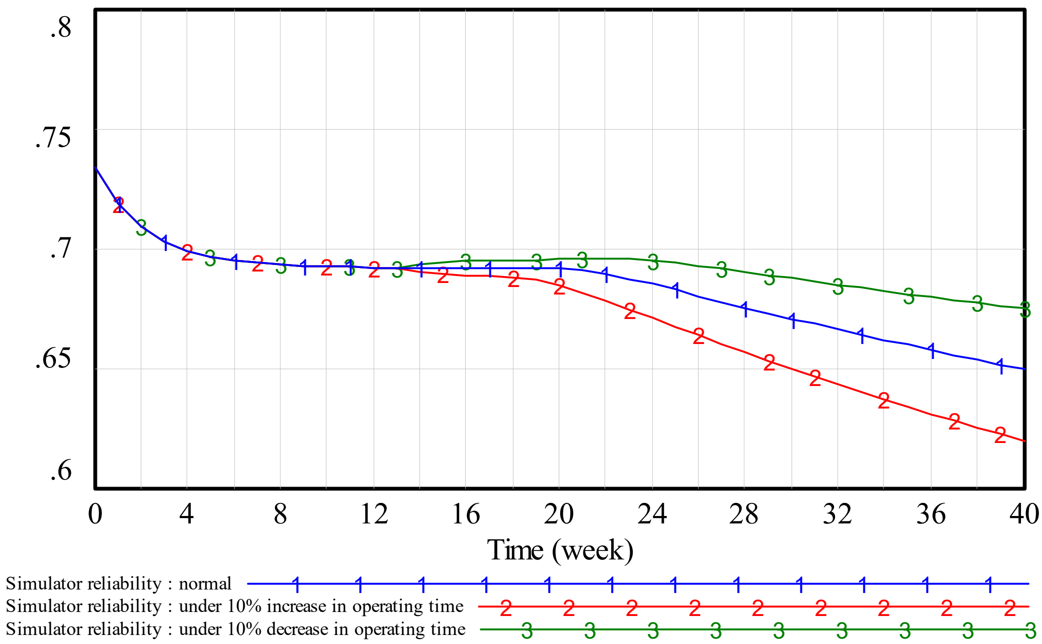

Figure 6. Simulated Effects of Operating Time on Reliability over Time

Simulation of Backup Part Supply Policies

Simulator maintenance cannot be performed without a supply of new parts; this would affect the training process. Over time, simulator maintenance is complicated by diminishing equipment and part supplies and long procurement times. In response, the air force should develop backup part supply policies for inventory management to ensure the required parts are available. This would decrease the number of administrative and transportation tasks required to procure parts and ensure an ample supply of parts during simulator malfunction. We used the model to simulate the respective effects of a 20% increase and decrease in backup supply on reliability (Figure 7). The results reveal that an increase in backup supply would ensure timely simulator maintenance, thereby maintaining reliability, whereas a decrease would prevent timely maintenance, resulting in a decrease in reliability.

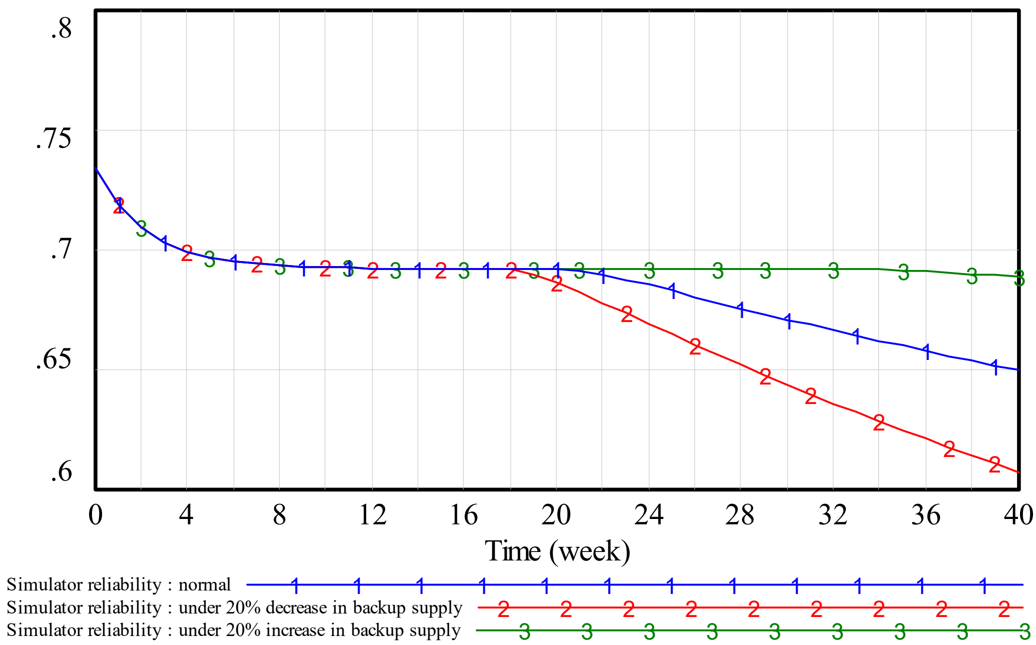

Figure 7. Simulated Effects of Backup Supply on Reliability over Time

Simulation Comparison and Sensitivity Analysis

Figure 8 presents the simulated effects of operating time and backup supply on reliability over time. The effect of backup supply on reliability is stronger than that of operating time. When operating time decreases, reliability briefly remains the same but ultimately decreases when backup supply decreases because of the lack of parts. With a sufficient backup supply, reliability remains the same for a long period.

We randomly selected ranges of the operating time and backup supply coefficients to conduct several simulations. A sensitivity analysis was performed to determine the effects of operating time and backup supply on reliability (Figure 9) and maintenance cost (Figure 10). Variation in maintenance cost under various policies presented graphically can effectively convey the behavior boundaries of the model and robustness of each policy.

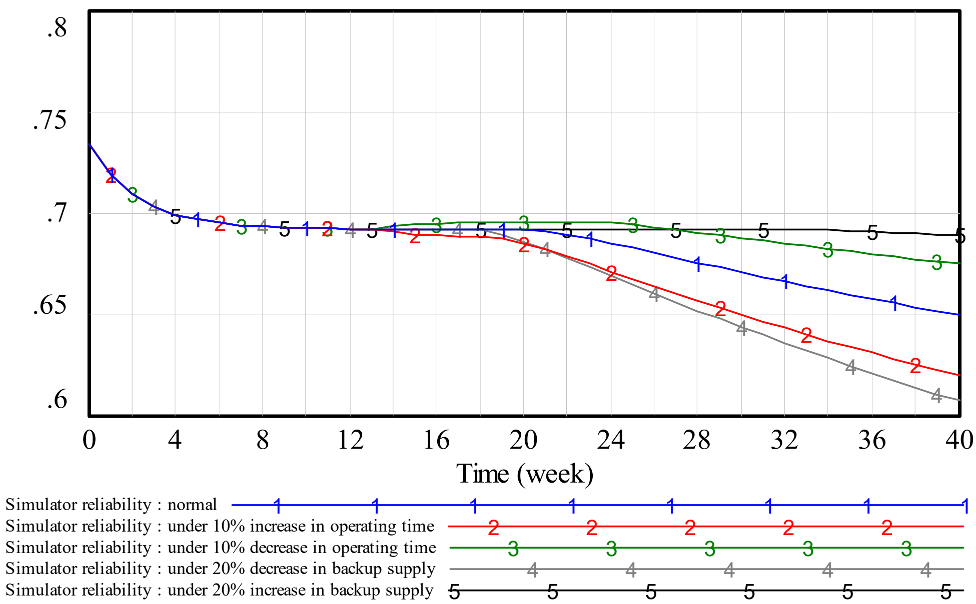

Figure 8. Simulated Effects of Operating Time and Backup Supply on Reliability over Time

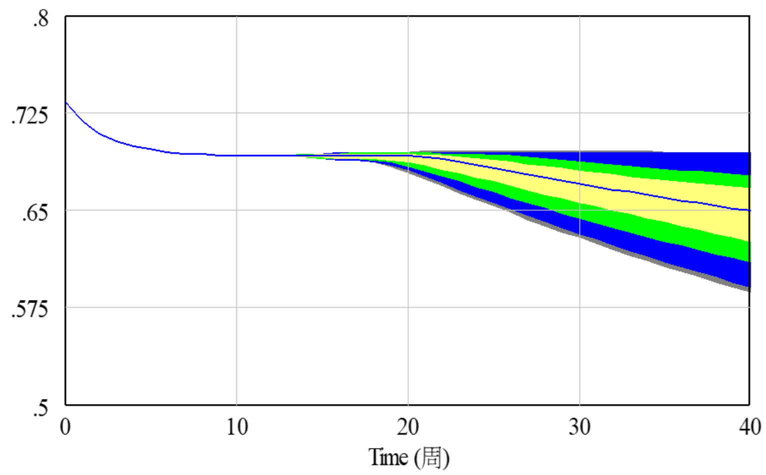

Figure 9. Sensitivity of Simulator Reliability over Time

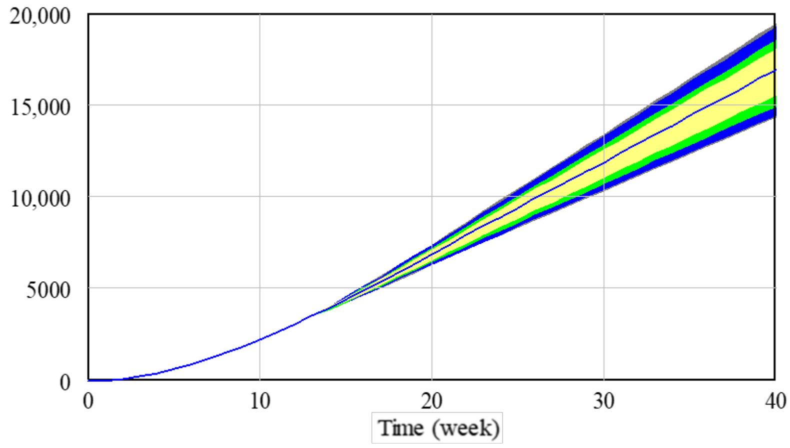

Figure 10. Sensitivity of Simulator Maintenance Cost over Time

Conclusion

Frequent simulator use may increase malfunction frequency, and a decrease in backup supply increases the difficulty of procuring parts and maintenance over time, which affects pilot training. This study employed the AT-3 high-end flight training simulator, the main flight training simulator used by the Taiwan air force, as a reference case. Short operating times and ample backup supplies ensure simulator reliability. In addition, the effects of backup supply policies on reliability are stronger than those of operating time policies. Although reducing operating time briefly ensures reliability, it eventually decreases with diminishing part supply. Therefore, inventory management policies related to backup supplies must be developed. Procuring spare parts in advance can decrease the difficulty of procuring parts due to diminishing suppliers. In addition, the number of administrative and transportation tasks required to procure parts can be reduced, and delays can be avoided, thus ensuring long-term simulator reliability.

Because simulator maintenance and parts inventory management involve numerous factors, a comprehensive and systematic strategy must be used for analysis. Subsequent studies on flight simulators can adjust the structure and variables of our model to explore the effects of simulator maintenance and parts inventory management strategies. Because maintenance cost also affects simulator maintenance, subsequent studies can use maintenance cost as a key variable in the model.

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