NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

OPTIMIZING AMMUNITION MANAGEMENT IN SINGAPORE

by

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September 2023

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2023	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE OPTIMIZING AMMUNITION MANAGEMENT IN SINGAPORE	**5. FUNDING NUMBERS**
6. AUTHOR(S) Wei Tien Chea	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

Ammunition is crucial to Singapore's defense readiness and national security, especially considering global events like the Russia–Ukraine conflict. Challenges faced by Singapore include low peacetime usage, restricted storage capacities, and significant disposal costs of obsolete ammunition, highlighting a need for efficient ammunition stockpile management. Our thesis introduces an optimization model to guide procurement strategies, determine optimal resource allocation between local production and overseas purchases, and recommend appropriate stockpile quantities to optimize the overall life cycle cost of ammunition. Our model further analyzes the implications of modulating production rates, available component quantities for local production, base production units for an operational production department, and transition expenses of production from dormant to operational states. Leveraging linear programming, our study analyzes 30 specific ammunition items, gauging them against local production proficiencies. By incorporating modular storage management, our model ensures a balance between maintaining a robust ammunition stockpile and cost efficiency. Our model therefore presents our ammunition stockpile manager with an invaluable tool tailored for enhanced ammunition management.

14. SUBJECT TERMS decision-support tool, resource optimization, ammunition stockpile, military capital spending	**15. NUMBER OF PAGES** 65
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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OPTIMIZING AMMUNITION MANAGEMENT IN SINGAPORE

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Ammunition is crucial to Singapore's defense readiness and national security, especially considering global events like the Russia–Ukraine conflict. Challenges faced by Singapore include low peacetime usage, restricted storage capacities, and significant disposal costs of obsolete ammunition, highlighting a need for efficient ammunition stockpile management. Our thesis introduces an optimization model to guide procurement strategies, determine optimal resource allocation between local production and overseas purchases, and recommend appropriate stockpile quantities to optimize the overall life cycle cost of ammunition. Our model further analyzes the implications of modulating production rates, available component quantities for local production, base production units for an operational production department, and transition expenses of production from dormant to operational states. Leveraging linear programming, our study analyzes 30 specific ammunition items, gauging them against local production proficiencies. By incorporating modular storage management, our model ensures a balance between maintaining a robust ammunition stockpile and cost efficiency. Our model therefore presents our ammunition stockpile manager with an invaluable tool tailored for enhanced ammunition management.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOE	Approval of Expenditure
GENMOD	General Modeling
GPSS	General Purpose Simulation System
KPS	Kellogg Planning System
MINDEF	Ministry of Defence
NEQ	Net Explosive Quantity
UNODA	United Nations Office for Disarmament Affairs

EXECUTIVE SUMMARY

With the evolving challenges of ammunition management, our thesis introduces an optimization model to provide comprehensive recommendations to manage the cost involved in the life cycle of ammunition stockpiles. Our model recommendations encompass the procurement approach, the balance between local manufacturing and overseas purchases, and the management of ammunition stockpiles in components or fully assembled form. This aims to reduce ammunition life cycle costs. By including modular storage within its design, our model ensures not only sufficient stockpile but also cost efficiency.

A notable aspect of our model lies in its detailed approach to mothballed facility management. It quantifies the costs involved when either reactivating or deactivating these production lines and recommends a cost-effective approach. Further supporting its real-world applicability, our model has a flexible design. It integrates penalty costs associated with potential discrepancies like stockpile surpluses or deficits due to production rates. Such an adaptive approach provides outcomes that reflect the challenges and needs of ammunition management scenarios.

In addition, our model has robust constraints that ensure optimal functionality. Inventory considerations span from tracking the inventory year on year and factoring in replenishments to accounting for various consumption determinants. Complementing the constraints is the model’s considerations for storage optimization, which also assesses storage compatibility between stored items, ensuring safe and sufficient storage. Our model verifies that shipment demands are met by sufficient holding, which are replenished either through local production or overseas purchase.

To perform these analyses, our model uses integer linear programming to analyze 30 ammunition items, considering local manufacturing potential. It recommends the quantity to produce or assemble, factoring in associated costs, and determines the optimal year for production by evaluating the production rate and disposal costs arising from shelf-life expiration. Notably, our model favors local production for product with lower cost of

local production due to its cost advantage over overseas purchases. In contrast, for product with higher cost of local production, the model leans towards overseas procurement because of its cost-effectiveness.

We test our model's sensitivity with a series of scenarios: One explores the implications of reduced production rates, suggesting a pivot towards overseas acquisitions. Another scenario, taking into consideration component availability, indicates a balanced preference for both local and overseas purchase. Additional scenarios, ranging from minimum production requirements to the cost involved in reactivating mothballed facilities, highlight our model's versatility and adaptability.

In conclusion, our model effectively provides recommendations for optimizing resource utilization and minimizing the overall life cycle cost associated with ammunition management. Our model demonstrates its capability by recommending the most suitable time period for both local production and overseas procurement and the most favorable order quantities, evaluating the viability of maintaining a production department to fulfil product requirements and the feasibility of reactivating a previously mothballed production department.

ACKNOWLEDGMENTS

I am deeply grateful to Professor Gerald Brown, whose mentorship and expert guidance has greatly influenced my thesis. His insightful feedback and endless patience throughout this journey have been invaluable.

I would also like to express my heartfelt gratitude to Professor Louis Chen for his unwavering support, dedication, insightful discussions, and patience throughout this journey.

In addition, I would like to thank all my friends who provided unwavering encouragement, their support has kept me motivated.

Last but certainly not least, I extend my heartfelt thanks to my loving husband, Xavier. His unwavering support, understanding, and constant encouragement have been my greatest motivation throughout this challenging yet incredibly rewarding journey.

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I. INTRODUCTION

This chapter establishes the context, addresses challenges, highlights problem significance, and outlines the thesis scope. It explains ammunition stockpile management fundamentals, emphasizes its complexities, and underscores its pivotal role in national defense. The chapter concludes by highlighting the thesis approach in tackling these challenges.

A. STRATEGIC AMMUNITION STOCKPILE MANAGEMENT

Singapore Army maintains a strategic ammunition stockpile based on a budget allocation from the Approval of Expenditure[1]; valid for eight to 12 years, with a review conducted every three to five years. The activation of planned purchases to replenish and refresh the stockpile depends on the production lead time of the manufacturer of each item. As part of the review, the ammunition planner develops a schedule to determine the minimum baseload quantities to be maintained for operational readiness and peacetime consumption. Peacetime consumption usually involves meeting training demands, testing, and disposal of unserviceable ammunition. The plan would also include the envisaged desired quantity to be built up for full operational capability.

The stockpile planner would trigger the procurement of an ammunition item via the procurement officer as part of the review conducted every three to five years. The procurement officer ensures a robust procurement plan by preparing a tender evaluation to determine the most suitable local and overseas manufacturers, based on factors such as meeting technical specifications, value for money, and reliable track records. The production lead time of each item for each manufacturer varies between 12 to 24 months depending on the quantities purchased, complexity of production, manufacturing

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[1] Approval of Expenditure (AOE) is a process in the Ministry of Defence (MINDEF) in Singapore where a proposed expenditure is evaluated and approved before it can be incurred. The purpose of AOE is to ensure that resources are used efficiently and effectively, and that there is accountability for the use of public funds. The evaluation considers factors such as the need for the expenditure, the feasibility of the proposal, and its alignment with the strategic objectives of MINDEF. The AOE process continues throughout the implementation phase, with regular monitoring and reporting to ensure that the expenditure is in line with the approved budget and objectives.

equipment, and manpower capacity of each manufacturer. Generally, a purchase contract includes a delivery schedule, specific quantity and a value for money pricing proposal. There could also be an option quantity for future deliveries at the agreed pricing, if exercised.

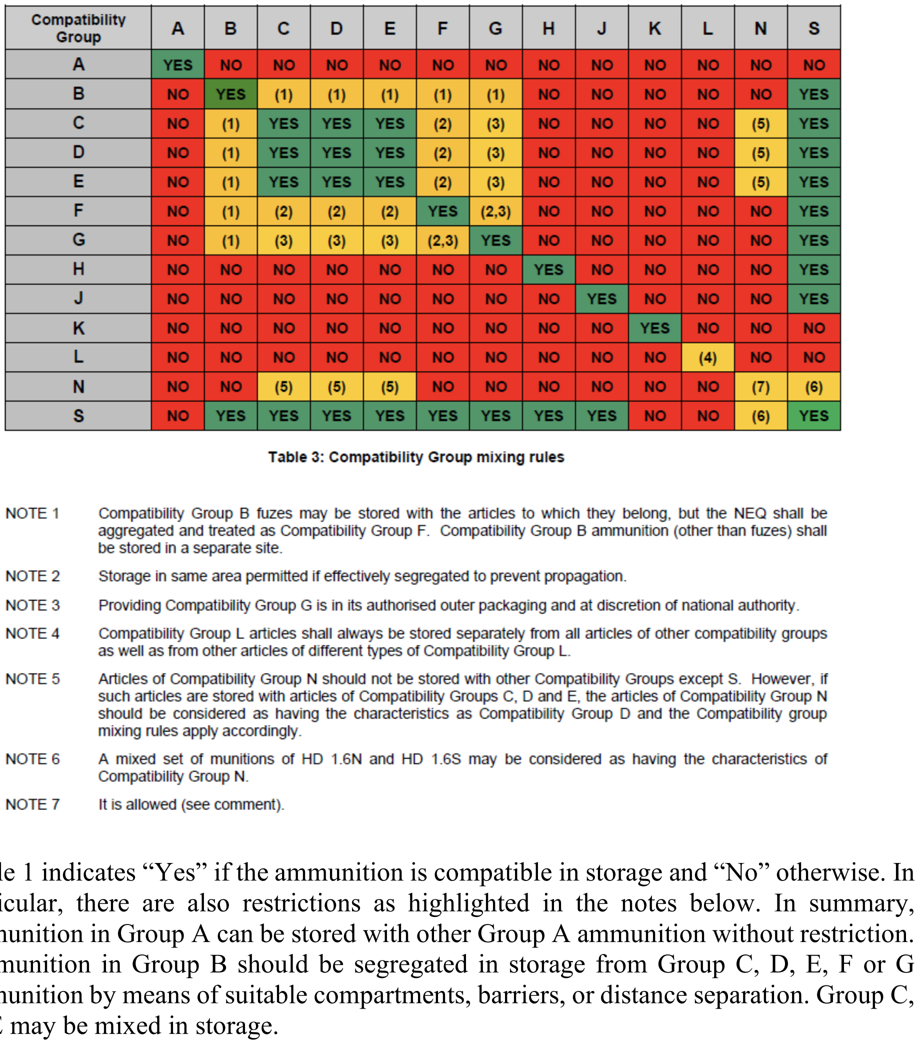
B. LOCAL PRODUCTION CAPABILITY AND CHALLENGES

Local ammunition production capability tends to only be built to cater to peacetime demands. Due to the life cycle of the ammunition and its demand, production machineries may not be utilized regularly. Each machine can be expected to be mothballed and periodically reactivated and exercised to retain functionality and may also be used to conduct operational readiness exercises. Production lines often share factory spaces, making the production of some ammunition types mutually exclusive with other types. There are usually significant costs to maintain production capability due to the need to maintain its functionality with regular maintenance, warming up the production line from mothball storage, and changing it to produce alternate ammunition types.

Singapore's local manufacturer maintains production facilities and qualified personnel and ensures the sustenance of workforce and maintenance of the production line by expanding its operations to support global ammunition sales for items such as 40 millimeter, 120 millimeter and 155 millimeter munitions. The local manufacturer is also involved in services such as ammunition testing and disposal.

C. SAFETY AND STORAGE REQUIREMENTS FOR AMMUNITION

Ammunition is a unique commodity that needs to adhere to stringent storage safety requirements. Storage facilities are designed to protect against explosive propagation and to withstand blast and shock. They are built far from populated areas or underground for horizontal blast protection and vertical blast relief. Therefore, this requirement results in limited storage space available for ammunition and this problem is exacerbated by the limited land space in Singapore. In addition, segregated storage will be required to separate selected ammunition types to reduce the effect of explosion or deflagration and the mixing rules are to be adhered to based on the Storage Compatibility Groups as indicated in Figure 1. The Storage Compatibility Groups are a system used to identify which types of ammunition can be safely stored together based on their potential hazard characteristics as classified in the compatibility group. Refer to Table 1 for the description of each compatibility group as extracted from International Ammunition Technical Guidelines (UNODA, 2021).



Compatibility Group	A	B	C	D	E	F	G	H	J	K	L	N	S
A	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
B	NO	YES	(1)	(1)	(1)	(1)	(1)	NO	NO	NO	NO	NO	YES
C	NO	(1)	YES	YES	YES	(2)	(3)	NO	NO	NO	NO	(5)	YES
D	NO	(1)	YES	YES	YES	(2)	(3)	NO	NO	NO	NO	(5)	YES
E	NO	(1)	YES	YES	YES	(2)	(3)	NO	NO	NO	NO	(5)	YES
F	NO	(1)	(2)	(2)	(2)	YES	(2,3)	NO	NO	NO	NO	NO	YES
G	NO	(1)	(3)	(3)	(3)	(2,3)	YES	NO	NO	NO	NO	NO	YES
H	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
J	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	YES
K	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO
L	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	(4)	NO	NO
N	NO	NO	(5)	(5)	(5)	NO	NO	NO	NO	NO	NO	(7)	(6)
S	NO	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	(6)	YES

Table 3: Compatibility Group mixing rules

NOTE 1	Compatibility Group B fuzes may be stored with the articles to which they belong, but the NEQ shall be aggregated and treated as Compatibility Group F. Compatibility Group B ammunition (other than fuzes) shall be stored in a separate site.
NOTE 2	Storage in same area permitted if effectively segregated to prevent propagation.
NOTE 3	Providing Compatibility Group G is in its authorised outer packaging and at discretion of national authority.
NOTE 4	Compatibility Group L articles shall always be stored separately from all articles of other compatibility groups as well as from other articles of different types of Compatibility Group L.
NOTE 5	Articles of Compatibility Group N should not be stored with other Compatibility Groups except S. However, if such articles are stored with articles of Compatibility Groups C, D and E, the articles of Compatibility Group N should be considered as having the characteristics as Compatibility Group D and the Compatibility group mixing rules apply accordingly.
NOTE 6	A mixed set of munitions of HD 1.6N and HD 1.6S may be considered as having the characteristics of Compatibility Group N.
NOTE 7	It is allowed (see comment).

Table 1 indicates “Yes” if the ammunition is compatible in storage and “No” otherwise. In particular, there are also restrictions as highlighted in the notes below. In summary, ammunition in Group A can be stored with other Group A ammunition without restriction. Ammunition in Group B should be segregated in storage from Group C, D, E, F or G ammunition by means of suitable compartments, barriers, or distance separation. Group C, D, E may be mixed in storage.

Figure 1. Segregated Storage Compatibility Group. Source: UNODA (2021)

Table 1. Ammunition Compatibility Groups. Source: UNODA (2021)

Compatibility Group	Description	Examples
A	Primary explosive substance.	Examples are lead azide, lead styphnate, mercury fulminate, tetracene, dry RDX, and dry PETN.
B	Articles containing a primary explosive substance and not containing two or more effective protective features. Some articles, such as detonators for blasting, detonator assemblies for blasting and primers, cap-type, are included, even though they do not contain primary explosives.	Examples are detonators, blasting caps, small arms primers, and fuses without two or more safety features.
C	Propellant explosive substance or other deflagrating explosive substance or article containing such explosive substance.	Examples are single-, double-, triple-based, and composite propellants, rocket motors (solid propellant), and ammunition with inert projectile.
D	Secondary detonating explosive substance or black powder or article containing a secondary detonating explosive substance, in each case without means of initiation and without a propelling charge, or article containing a primary explosive substance and containing two or more effective protective features.	Examples are bulk TNT, Composition B, wet RDX, bombs, projectiles, warheads, or fuzes with two or more safety features.
E	Article containing a secondary detonating explosive substance without means of initiation, with propelling charge (other than one containing a flammable liquid or gel or hypergolic liquids).	Examples are artillery ammunition, rockets, or guided missiles.
F	Article containing a secondary detonating explosive substance with its own means of initiation, with a propelling charge (other than one containing a flammable liquid or gel or hypergolic liquids) or without a propelling charge.	An example is a rocket propelled grenade.
G	Pyrotechnic substance, or article containing a pyrotechnic substance, or article containing both an explosive substance and an illuminating, incendiary, tear- or smoke-producing substance (other than a water activated article or one containing white phosphorus, phosphides, a pyrophoric substance, a flammable liquid or gel, or hypergolic liquids).	Examples are flares, signals, incendiary or illuminating ammunition, and other smoke and tear producing devices.
H	Article containing both an explosive substance and white phosphorus.	Examples are WP, plasticized white phosphorus (PWP), or other ammunition containing pyrophoric material.
S	Substance or article so packed or designed that any hazardous effects arising from accidental functioning are confined within the package unless the package has been degraded by fire, in which case all blast or projection effects are limited to the extent that they do not significantly hinder or prohibit fire-fighting or other emergency response efforts in the immediate vicinity of the package.	Examples are small arms cartridges (ball), explosive switches or valves.

Ammunition is also classified based on hazard division as indicated in Table 2. Typically, the Singapore Army is equipped with four main groups of ammunition with hazard divisions 1.1 to 1.4 and the storage facilities are classified into the four main divisions.

Table 2. Hazard Division. Source: UNODA (2021)

Hazard Division	Description	Elaboration
1.1	Ammunition that has a mass explosion hazard.	Ammunition items with a Hazard Division of 1.1 are extremely hazardous and require the highest level of security and safety precautions
1.2	Ammunition that has a projection hazard but not a mass explosion hazard.	Ammunition items with a Hazard Division of 1.2 are highly hazardous and also require a high level of security and safety precautions
1.3	Ammunition that has a fire hazard and either a minor blast hazard or a minor projection hazard or both, but not a mass explosion hazard.	Ammunition items with a Hazard Division of 1.3 are moderately hazardous
1.4	Ammunition that presents no significant hazard.	Ammunition items with a Hazard Division of 1.4 are low-level hazardous

Hazard Division 1 is the highest hazard division and is further divided into four sub-divisions based on the level of hazard. The Hazard Division of an explosive affects its Net Explosive Quantity[2] (NEQ) limit, with lower Hazard Division items having higher NEQ limits and higher Hazard Division items having lower NEQ limits. This is based on the potential for harm and the safety requirements for handling and storage of explosives.

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[2] NEQ limit refers to the maximum amount of explosive material that is permitted to be stored or transported in a particular location, such as a magazine, container, or vehicle. The NEQ limit is based on the hazard classification of the explosive material, as well as the specific regulations and guidelines that apply to the storage or transportation of explosives. The NEQ limit is established to ensure that the amount of explosive material present in a given location does not exceed the safe handling and storage capacity of that location and that the risk of accidental explosion or other incidents is minimized.

Ammunition management is based on production lots to facilitate defective ammunition investigation and disposal if necessary. Each ammunition lot is produced with a fixed reliable lifetime. If the ammunition item is deemed unserviceable and needs to be removed from the inventory, it will be accounted for on the annual revision for the three-to-five-year plan. In addition, the ammunition will be disposed of if it is not consumed within its serviceable shelf life.

D. PROBLEM SIGNIFICANCE

Strategic ammunition inventory management is critical in Singapore's defense readiness and plays a vital role in safeguarding national sovereignty and security interests. This highlights the significance of cost-effective ammunition stockpile management for sustenance. Recent global events, particularly the Russia-Ukraine war, have also highlighted the criticality of rapid ammunition replenishment for military readiness (Bertrand, Liebermann and Hansler, 2023). Swift military stock replenishment is imperative for enhancing the nation's readiness to respond to potential threats effectively and sustain in a war (Ryan, 2023). Therefore, failure to maintain an optimal ammunition stockpile can compromise our defense capability and undermine our security posture.

From a defense budget perspective, traditional ammunition stockpiling will incur substantial costs over its lifetime. Stockpiled ammunition is primarily reserved for operational readiness, and low utilization during peacetime training consequently results in low demands and production rates at the industrial plant. Expired ammunition disposal also incurs significant disposal costs due to overseas disposal requirements. This is due to the limited land space in Singapore and expenses required to demilitarize the ammunition. Therefore, it is essential to adopt a cost-effective strategy and prudent budget allocation to sustain defense capabilities. The optimization of resources involved in ammunition management will not just merely improve the administrative process but will also be a strategic necessity for maximizing the return on investment in defense resources.

In addition, the significance of this issue also extends to the broader defense capability of Singapore Army whereby an outdated or insufficient ammunition stockpile can result in sub-optimal military effectiveness and undermine our ability to effectively deter potential adversaries. An optimized and robust ammunition stockpile will be critical in maintaining a strong and credible posture, ensuring the protection of national security interests.

The need for a robust ammunition stockpile calls for the need for innovative stockpile management including modular ammunition management. This involves the storage of ammunition quantities that are only required during wartime in component form and having our local production facilities assemble them when needed. Each ammunition component has a distinct shelf life. Managing ammunition in component form allows us to replace only the shelf life-limiting component at a fraction of the total unit cost if the complete round is not required to be assembled. This results in substantial cost avoidance. Figure 2 provides an illustration of modular ammunition management. This figure presents an example of a fragmentation grenade, highlighting the impact of modular storage on shelf life and cost avoidance. When the grenade is assembled, its shelf life is determined by the shelf-life limited component. However, storing the grenade in component form or modular form allows for the replacement and disposal of only the shelf life limiting component, significantly reducing disposal costs compared to replacing the entire assembled product. This maximizes the usable shelf life of other components that are not expired yet.

Storing the grenade in modular form also enables design enhancements, providing the flexibility to replace a specific component without being locked into the same design for an extended period. In this example, the detonator serves as the shelf life limiting component. By replacing the detonator instead of the entire assembled fragmentation grenade, cost avoidance of up to 60% of the ammunition unit cost can be achieved over 30 years.

Furthermore, modular storage allows for the replacement of the grenade body with other variants, such as a less lethal or more lethal variant, if the need arises. This enhances flexibility in design changes and ensures adaptability to evolving defense requirements.

The implementation of modular storage for fragmentation grenades offers significant cost savings and increased flexibility, making it a promising solution for optimizing ammunition shelf life and design versatility. This suggests that the local production facilities must have the necessary resources and capability required to assemble the required stockpile within a stipulated length of time.

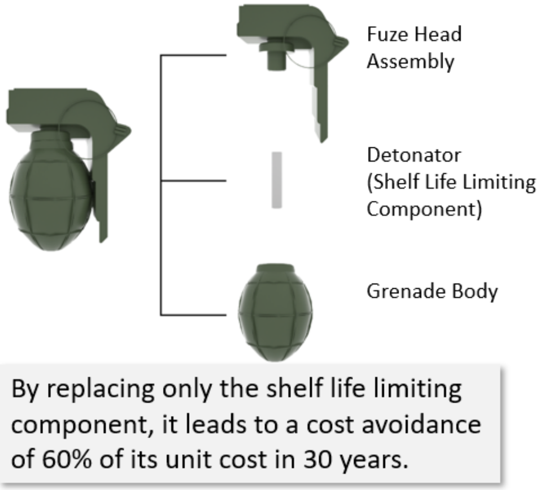

Figure 2. Illustration of Cost Avoidance from Replacement of a Shelf-life Limiting Component

Moreover, the complexity of decision-making arises due to the involvement of diverse users perhaps with different objectives across the Singapore Army and stockpile managers. Coordination challenges and varying demands highlight the need to have a systematic approach to optimize the allocation and utilization of resources for ammunition management.

E. SCOPE OF THE THESIS

This thesis develops an optimization model to help mitigate the challenges of ammunition stockpile management, given the importance of ammunition stocks to national defense. The objective is to address the critical decision-making aspects, which include determining the procurement approach and timing such as to produce locally or buy overseas, production rates and resource allocation.

In addition, this thesis presents an innovative method for enhancing cost-effectiveness and readiness by storing ammunition quantities required during wartime in component form and leveraging local production capabilities for assembly when the need arises. This strategic approach is expected to generate substantial cost avoidance and resource efficiency.

An optimization model strikes a balance between assuring a robust ammunition stockpile for national defense readiness while maximizing cost savings through the implementation of modular storage. The incorporation of these strategies is expected to result in significant advancements in ammunition management and aligns with the overarching goal of enhancing the nation's defense capabilities.

Ammunition items have been selected based on the local production facility's capability to assemble the components just-in-time. Due to security classification and sensitivity of the data, the thirty items are renamed in codes and the following data will be generated using Excel's (Microsoft Corporation, 2018) random number generator for modeling purposes:

1. Minimum and Full Stockpile Required
2. Minimum and Maximum Production Rate
3. Yearly demand
4. Maximum shelf life for each product
5. Component and assembly cost
6. Purchase cost
7. Storage space required for each item
8. Storage compatibility group for each item
9. Disposal costs
10. Transition costs for mothballed production facilities
11. Penalty cost for shortfall and surplus quantities due to limited production rate

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II. LITERATURE REVIEW

The following literature provides insights into managing military spending, capital planning, and production lines using optimization techniques. The studies address challenges such as a declining workload at military facilities, portfolio optimization under budget constraints, and achieving cost-effectiveness in industrial production. However, the literature reviewed does not directly address the challenges involved in the entire life cycle of ammunition management.

A. OPTIMIZING THE CAPACITY AND OPERATION OF U.S. ARMY AMMUNITION PRODUCTION FACILITIES

A study by Bayram (2002) addresses the challenges of the declining workload at U.S. arsenals and ammunition plants since the end of the Cold War, resulting in underutilized capacity and increased per-unit costs. The study's goal is to reconfigure ammunition production facilities and stabilize production rates while fulfilling peacetime and replenishment requirements. To tackle these challenges, the study introduces a integer linear programming model as a decision support system, proposing optimal yearly operating modes for each ammunition installation, structure and process center over a 10-year planning horizon, considering budget, management, and capacity constraints.

By scheduling decisions on when and how to reconfigure installations, structures, and process centers, as well as managing capacity utilization, production rates and resource allocation, the study addresses the challenges faced by the ammunition production base. This includes underutilized capacity, increased per-unit costs, and the need for reconfiguration and modernization.

By optimizing the sequence and timing of these actions, Bayram shows that the decision-support tool improves the overall performance and readiness of U.S. Army arsenals and ammunition plants in managing the production and stockpiling of ammunition and ordnance items. The approach can be applied to our thesis where we also consider the optimization of ammunition production and are faced with similar challenges in terms of the need to fulfil ammunition demands while keeping the production costs involved sustainable.

In addition, Bayram's model addresses the complexities involved in the optimization of 16 different ammunition manufacturing installations, 34 structures, 19 process centers and nine process types over a 10-year horizon. His model also considers the fixed and variable possession and operating costs while meeting replenishment and demand requirements for production of ammunition items. Bayram also states the scale of ammunition planning involved, which is over 5 million tons of conventional ordnance with an estimated value of about $80 billion as of the year of 1994.

B. OPTIMIZING MILITARY CAPITAL PLANNING

In a study by Brown, Dell and Newman (Brown et al., 2004), linear integer programming is applied to address military capital planning challenges, such as portfolio optimization under budget constraints. This study describes a binary knapsack model that uses a linear integer program to maximize total value while staying within budget constraints. According to this research, in real-world scenarios, such models take into account variables such as decisions to purchase weapon systems and the quantity to purchase. In the study, the models account for continuous quantities, weapon system contributions, and the influence of numerous factors on decision-making in the military scenario.

From the study, the U.S. Air Force and Navy's use of the capital-planning models demonstrate the viability of solving complex problems with thousands of variables and constraints. These linear programming models provide near-optimal solutions within a short computation time, allowing decision-makers to make informed decisions based on data. This research emphasizes the significance of leveraging linear programming in optimizing military spending and this can also be applied to ammunition stockpile spending.

C. THE KELLOGG COMPANY OPTIMIZES PRODUCTION, INVENTORY, AND DISTRIBUTION

In a study by Brown et al. (2001), the use of linear programming in industrial planning and optimization has proven to be instrumental in achieving cost effectiveness and streamlining complex operations. This study provides valuable insights into how linear programming techniques can be applied to guide manufacturing production and distribution decisions.

The Kellogg Planning System (KPS) model described in the study deals with various constraints within a plant, such as processing line capacities, packaging line capacities, and product flow-balance. The model in the study also takes into account intermediate products and semi-processed items, enabling efficient shipment between plants for further processing or packaging. To address uncertainties in demand, KPS employs planned safety stocks as a buffer, ensuring product availability during promotional periods. The model coordinates processing and packaging lines to efficiently meet demand throughout each time interval.

The application of linear programming in KPS illustrates the potential for optimizing resource allocation and production capacity. In addition, by incorporating penalty terms for violating capacities, demand, and safety stocks, linear programming can help minimize costs and ensure readiness while meeting dynamic demands. The tactical version of KPS can aid in long-term planning and guide capacity expansion or consolidation decisions, as seen in the successful consolidation project at Kellogg.

By drawing lessons from Kellogg's experience with KPS, we will explore how linear programming can be leveraged for resource allocation, capacity planning, and product flow-balance while meeting dynamic demands and optimizing military spending in ammunition stockpile management.

D. SIMULATION OF AMMUNITION PRODUCTION LINES

Menke and Tran (1982) analyze the ammunition production capability of a given metal parts line through computer simulation. The study compares existing simulation models and selects two suitable programs, General Purpose Simulation System (GPSS) (Gordon, 1978) and General Modeling (GENMOD) (Loniewski, 1978). Both models are discrete-event simulation models, which are appropriate for simulating metal parts ammunition lines with individual discrete events that occur during the production process such as loading of raw materials, operation of machines, and the unloading of finished products and waiting time of parts or materials before they are processed by a machine or operation in the production process.

This study proves the use of computer simulation, particularly the GENMOD program, to be effective in predicting monthly production rates for metal parts production lines. It allows line and sensitivity analysis, enabling designers to optimize throughput and facility cost before construction. Line analysis involves analyzing the production line to identify potential bottlenecks that can be addressed by adjusting buffer inventory that is available to handle variations in production rates and processing time or production rates of individual machinery. Sensitivity analysis entails varying the input parameters of the simulation model to determine how alterations to these parameters impact the output, such as the monthly production rate. By conducting sensitivity analysis, the designer can identify the most important input parameters and concentrate on increasing their accuracy. The simulation identifies the need for preventive maintenance programs and the advantages of multiple machines producing at a lower rate for better reliability.

The findings highlight the importance of accurate input data, preventive maintenance, and appropriate buffer sizes in optimizing production rates and facility performance. The use of simulation can be applied to enhance manufacturing efficiency in ammunition production.

E. KEY LEARNING POINTS FROM LITERATURE REVIEW

While previous studies have addressed the optimization of military spending, logistics, production lines and management of ammunition production plant, there is a noticeable gap in research regarding the optimization of the entire life cycle of ammunition management, which includes production, storage, and disposal costs.

III. MODEL DEVELOPMENT

A. INTRODUCTION

There are several economic, industrial production capability and operational readiness considerations used to determine whether to purchase ammunition from overseas or produce it locally, and whether the local production plant can fully assemble the ammunition from component form within some stipulated time.

The model here seeks to provide an optimization of the total life cycle cost borne by the Singapore Army by incorporating the multiple cost and storage factors listed below:

1. Local production cost that includes the cost of purchasing the components required and the assembly cost;
2. Overseas purchase cost;
3. Assembly cost when the assembly is activated in a time period;
4. Transition (opening and closing between time periods) costs of production plants;
5. Disposal cost of expired products;
6. Penalty costs from violating stockpile quantities required due to production rates;
7. Storage capacity of storage facilities; and
8. Storage compatibility considerations for each type of ammunition.

One crucial aspect addressed by the model is the management of mothballed facilities. The transition costs involved in either bringing a mothballed facility back to a state of readiness for production or shutting down an open facility, as well as maintaining an open or a closed facility, are accounted for in this model. Therefore, the state of production line needs to be tracked to determine the transition cost required from the prior time period (t-1) current time period (t). Transition costs are illustrated in Figure 3 where shows that it is most costly to transit from a closed state to an open state.

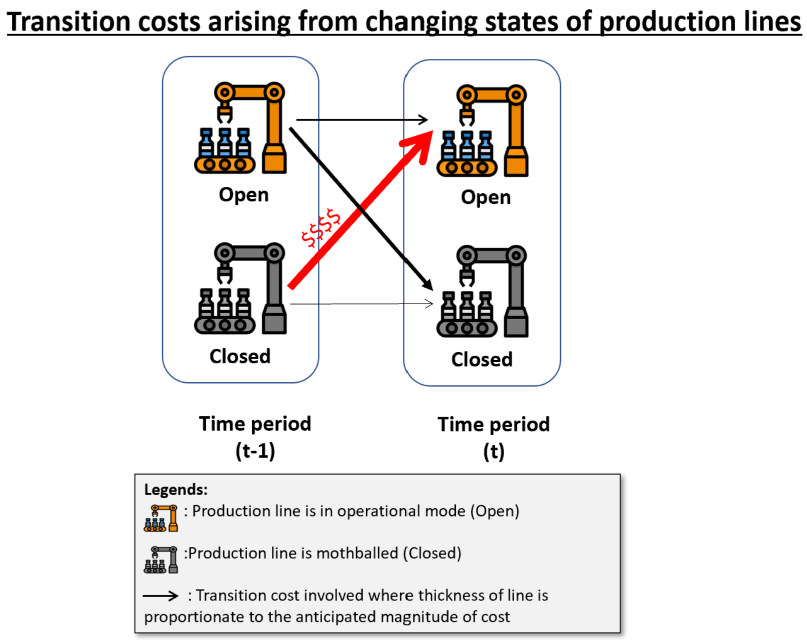

Figure 3. Illustration of Transition Cost from Changing States of Production Lines

Furthermore, the model is designed to be flexible, allowing for optimization by incorporating penalty costs with elastic variables for surplus and shortfall of stockpile quantities required. This approach permits constraints to be violated at a penalty cost, ensuring realistic and practical outcomes in ammunition stockpile management.

By exploring the model's objective and constraints, this chapter aims to develop a strategic approach to ammunition stockpile management.

B. MODEL OBJECTIVE

The objective function of the model evaluates the life cycle costs involved in ammunition stockpiling that includes the making, buying, assembling and transition cost of changing states of production plants; it also includes disposal costs and penalty costs for any violation of production requirements.

C. MODEL ASSUMPTIONS

The model relies on the following assumptions:

1. Discrete time periods. Although the operations involved are persistent over time, we assume discrete time periods over a finite time horizon for periodic review of the state of our system.

2. Disposal required after finite shelf life. We assume that each unit of each ammunition has a "born-on" date and may have a finite shelf life, after which disposal is necessary.

3. Known initial conditions. We assume that the initial inventory, age, and location of all our ammunition types are known.

4. Known end-states. We assume that the end state at the conclusion of our planning horizon has specified inventory levels of all ammunition types.

5. Production quantities are continuous. To facilitate mathematical modelling and analysis, it is assumed that production quantities are continuous. Ammunition unit quantities are large, so this assumption is innocuous.

6. Units that are at the end of their shelf life can still be used. The model assumes that units at their maximum age *during* a planning period of a 10-year horizon are still usable during that period to meet the required demand. By utilizing units at their maximum age, the model can ensure the effective utilization of available resources while meeting demand requirements.

7. Units reaching the end of shelf life to be disposed. It is assumed that unexpended units reaching their shelf life *at the end of a time period* will be disposed of at the start of next time period. By incorporating this assumption, the model can accurately reflect the dynamic nature of the ammunition stockpile and the necessity of managing expired units.

8. Product manufactured from component form has brand new shelf life. It is assumed that there is an agreement with the manufacturer to refresh components purchased through overseas sales such that product manufactured from such components has a brand-new shelf life.

Therefore, the shelf life of the assembled product would not be limited by the shortest shelf life of the component at the point of assembly.

9. Disposal cost of a component is to be excluded. It is assumed that the agreement with manufacturer takes into account the disposal of components under the manufacturer's responsibilities and costing. However, the disposal cost of assembled product is to be paid by Singapore Army.

D. MODEL FORMULATION

1. Indices [~cardinality]

$t \epsilon T$	Planning time horizon periods in the calendar year [~10]
$\tau \epsilon T$	Born-on period, where $\tau = t - \overline{age}, t - \overline{age} + 1, \dots, t$ ($\overline{age}$ is maximum age in periods)
$i \in I$	Component *i* [~90]
$j \in J$	Assembled product *j* [~30]
$i \in I_j$	Set of component units *i* required to create assembly *j* [~90]
$s \in \{0,1\}$	State closed, open for production facility during the prior time period *(t-1)* year
$\sigma \in \{0,1\}$	State closed, open for production facility during current time period, *t* year
$f \in F$	Set of storage facilities [~50]
$d \in D$	Set of production departments [~15]

2. Given Data [units]

$demand_{t,j}$	Units of demand to be met during time period *t* for each product *j* [units]
$B_{i,j}$	Bill of materials[3] [i-units of material per *j*-unit of product *j*] [units/units]
$\overline{units}_{j,t}$	Maximum production units per period for each product *j* [units/time]
$\underline{units}_{j,t}$	Minimum production units per period for each product *j* [units/time]
$\underline{pen}_{j,t}$	Penalty for shortfall of product *j* in time *t* below minimum required stockpile replenishment [S$/unit]
$\overline{pen}_{j,t}$	Penalty for surplus of product *j* in time *t* above maximum required stockpile replenishment [S$/unit]
$maxrate_{d,j}$	Maximum production rate of each production department *d* for product *j* [units/planning period]
$minrate_{d,j}$	Maximum production rate of each production department *d* for product *j* [units/planning period]
$compcost_{i}$	Cost of buying component *i* [S$/unit]
$makecost_{j}$	Cost of producing product *j* [S$/unit]
$buycost_{j}$	Cost of buying product *j* [S$/unit]
$disposalcost_{j}$	Cost incurred to dispose each product *j* [S$/unit]

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[3] The bill of materials refers to the list of all the components, sub-assemblies and quantities required to manufacture or assemble a product.

$transcost_{d,s,\sigma,t}$	Transition cost for each production department, *d* to move from state *s* (open or closed) to state sigma (open or closed) between time periods *t-1* and *t* [S$]
$space_j$	Burden rate required for product *j* [units^{-1}]. It is a fraction of the storage capacity required by each unit *j*. Each storage facility is assumed to have the same storage capacity.
$exclude_{j,j'}$	Signals that *j* and *j'* are mutually exclusive in storage when =1, 0 otherwise [binary]
$assemblycost_j$	Cost of assembling each unit of product *j* from components [S$/unit]
$\overline{age}_j$	Maximum age of product *j* (shelf life) [periods]
$minstockpile_{j,t}$	Minimum stockpile holding of each product *j* to be maintained [units]

3. Decision Variables [units]

$MAKE_{j,\tau}$	Quantity of product *j* manufactured *during time period* τ made from the product's respective components *i*. For products that are stored as components for modularity, they can be assembled to meet stockpile requirements when needed. [units]
$HOLD_{j,t,\tau}$	Quantity of component *i* or j manufactured during period τ and held in storage *at end of time period t*, ($HOLD_{j,0,\tau}$ is initial inventory for $t-\overline{age} \leq \tau \leq t$, $HOLD_{j,T,\tau}$ is ending inventory target)

$CAPACITY_{j,t,\tau,f}$	Quantity of product *j* held in storage facility *f at end of time period t*, manufactured during period τ [units]
$SHIP_{j,t,\tau}$	Quantity of product *j* shipped out to meet demand during *t* that was made in τ [units]
$SCRAP_{j,t,\tau}\|_{t=\tau+\overline{age}}$	Quantity of product *j* that was made in prior period τ that is to be discarded during later period *t* is at end of *t* $\overline{age}_j$ periods old) [units]
$ASSY_{i,t,\tau}$	Component units that are produced in tau and assembled during *t* [i-units]
$ASSY_{j,t,\tau}$	Product units that are assembled [*j*-units]
$OPEN_{d,t}$	Signal or control of manufacturing activity during period *t* [binary] ($OPEN_{0,d}$ is a state of manufacturing activity prior to start of planning horizon {0,1} for each production department *d*)
$TRANS_{d,s,\sigma,t}$	Tracks adjacent values of $OPEN_{d,t-1}$ and $OPEN_{d,t}$
$A_{j,t}$	Artificial variable for quantity of product *j* in time period *t*. It permits the minimum stockpile quantity to be violated at a penalty for each unit of violation. [units]
$S_{j,t}$	Slack variable for quantity of product *j* in time period *t*. It represents the buffer replenishment quantity for each product *j* within the planning period. [units]
$R_{j,t}$	Surplus variable for quantity of product *j* in time period *t*. It permits the maximum stockpile quantity to be violated at a penalty for each unit of violation. [units]

$BUY_{j,\tau}$	Quantity of product *j* purchased *during time period* τ [units]
$STORE_{j,t,f}$	Determines if product *j* in time period ***t*** can be stored in facility *f* [binary]

4. Formulation

Minimizing by choice of MAKE, BUY, SCRAP, ASSY, TRANS, A, R, the total cost of ammunition life cycle

$$
\begin{aligned}
\min_{MAKE,BUY,ASSY,TRANS,SCRAP,A,R} \Big[& \sum_{j}\sum_{t} makecost_j \times MAKE_{j,t} + buycost_j \times BUY_{j,t} \\
& + \sum_{\tau}\left(disposalcost_j \times \; SCRAP_{j,t,\tau}|_{t=\tau+\overline{age}}\right) \\
& + \left(\underline{pen_{j,t}} \times A_{j,t} + \overline{pen}_{j,t} \times R_{j,t}\right) \Big] \\
& + \sum_{i}\sum_{t} compcost_i \times ASSY_{i,t} \\
& + \sum_{d}\sum_{s}\sum_{\sigma}\sum_{t} trans_{d,s,\sigma,t} \times TRANS_{d,s,\sigma,t}
\end{aligned}
$$

a. Constraints

s.t.

1. Constraint (1) accounts for balance of flow into, during, and out of a time period. Prior inventory is added to current local manufacturing from components assembled to product *j* and purchase of product *j* in assembled form directly. Disposal of aged-out units that have reached shelf life and shipping out to satisfy demand is subtracted. The balance is the inventory at the end of the period.

$$HOLD_{j,t-1,\tau} + MAKE_{j,t} + BUY_{j,t} - SCRAP_{j,t,\tau}|_{t=\tau+\overline{age}} - SHIP_{j,t,\tau} = HOLD_{j,t,\tau}$$

$$\forall\, j \in J$$

$$\forall\, t \in T$$

$$\tau = (t-\overline{age}), (t-\overline{age})+1, \dots, t$$

2. Each constraint (2) assures that there is capacity to hold units in inventory at the end of a period. Each storage facility is assumed to have capacity of 1. *space_j* refers to the reciprocal storage consumption coefficient for each product *j*. For example, if each storage facility *f* is able to store 100 units of product *j*, the consumption coefficient will be represented as 1/100.

$$\sum_{\tau}\sum_{j} space_j \times CAPACITY_{j,t,\tau,f} \leq 1 \qquad \forall t \in T, \forall f \in F$$

3. Each constraint (3) assures that segregated storage is observed where only items that are compatible are stored together in the same storage facility, *f*.

$$STORE_{j,t,f} + STORE_{j',t,f} \leq 1 \qquad (j,j')|exclude_{j,j'}, \forall t \in T, \forall f \in F$$

$$STORE_{j,t,f} \in \{0,1\} \qquad \forall j \in J, \forall t \in T$$

4. Each constraint (4) assures that for each product *j*, which requires space, *space* is stored in one of the storage facilities.

$$\sum_{\tau} space_j \times CAPACITY_{j,t,\tau,f} \leq STORE_{j,t,f} \qquad \forall j \in J, \forall f \in F, \forall t \in T$$

5. Each constraint (5) assures that the total storage space required for each product *j* in each facility *f* is the total space taken in the facilities, *f*.

$$\sum_{\tau}\sum_{f} CAPACITY_{j,t,\tau,f} \geq \sum_{\tau} HOLD_{j,t,\tau} \qquad \forall j \in J, \forall t \in T$$

6. Each constraint (6) expresses the total shipment of units to satisfy demand of each product *j* during a period.

$$\sum_{\tau = t-\overline{age}_j, t-\overline{age}_j+1,\ldots,t} SHIP_{j,t,\tau} = \mathrm{demand}_{\mathrm{j,t}} \qquad \forall t \in T \; and \; \forall j \in J$$

7. Each constraint (7) expresses the units shipped to satisfy demand should be within the ammunition holding space available.

$$\sum_{\tau = t-\overline{age}_j, t-\overline{age}_j+1,\ldots,t} SHIP_{j,t,\tau} \leq \sum_{\tau} HOLD_{j,t,\tau} \qquad \forall t \in T \; and \; \forall j \in J$$

8. Each constraint (8) expresses the assembly of component units *i* drawn from inventory at the end of period *t-1* and assembled during period *t* into units *j*. This accounts for the inventory for components and assembled product. The age of all components and their assembly is then assumed to be the same.

$$B_{i,j}^{-1} ASSY_{i,t,\tau} = ASSY_{j,t,\tau} \quad = MAKE_{j,t} \qquad \forall j \in J, i \in I$$

$$\forall t \in T$$

$$\tau = t - \overline{age}_j, t - \overline{age}_j + 1, \ldots, t$$

9. Each constraint (9) requires exactly one of the four possible transition states between an immediately prior and current time period, from *t-1* to *t*.

$$\sum_{s,\sigma} TRANS_{d,s,\sigma,t} = 1 \qquad t = 2, \ldots, T \text{ and } d \in D$$

10. Each constraint (10) requires signalling the state of manufacturing in an immediately prior time period, including just prior to the start of the first time period in the planning horizon.

$$1 - \sum_{s} TRANS_{d,s,0,t} = OPEN_{d,t-1} \qquad \sigma \epsilon \{0,1\}, \forall t \in T, d \in D$$

$$\sum_{s} TRANS_{d,s,1,t} = OPEN_{d,t-1} \qquad \sigma \epsilon \{0,1\}, \forall t \in T, d \in D$$

11. Each constraint (11) requires signaling the state of manufacturing in a current time period.

$$1 - \sum_{\sigma} TRANS_{d,0,\sigma,t} = OPEN_{d,t} \qquad s \epsilon \{0,1\}, \forall t \in T, d \in D$$

$$\sum_{\sigma} TRANS_{d,1,\sigma,t} = OPEN_{d,t} \qquad s \epsilon \{0,1\}, \forall t \in T, d \in D$$

12. Each constraint (12) is an elastic constraint; it is a ranged constraint so that the lower or upper range can be violated at a penalty cost per unit of violation. An elastic constraint (12) signals or controls the amount of production and measures any violation of the ranges on production quantity. Slack variable $S_{j,t}$ is the allowable slack between the maximum production units and minimum production units deriving from production rate of each product j. Surplus variable, $R_{j,t}$ is the surplus quantity for each product j. $A_{j,t}$ is the shortfall quantity for each product j.

$$\underline{units}_{j,t}OPEN_{d,t} = MAKE_{j,t} + A_{j,t} + S_{j,t} - R_{j,t} = \overline{units}_{j,t}OPEN_{d,t}$$

$$\forall\, j \in J, \forall\, t \in T, \forall\, d \in D$$

13. The slack bounds below allow the amount of production to range between its elastic limits.

$$0 \le S_{j,t} \le \overline{units}_{j,t} - \underline{units}_{j,t} \qquad \forall j \in J \quad \forall t \in T$$

$$A_{j,t} \ge 0$$
$$R_{j,t} \ge 0$$

14. Each constraint (14) ensures that the held units meet the minimum stockpile level required for operational readiness.

$$\sum_{\tau} HOLD_{j,t,\tau} \ge minstockpile_{j,t} \qquad \forall j \in J \quad \forall t \in T$$

5. Discussion

The objective of the model is to express the overall cost of producing ammunition for the stockpile in Singapore dollars. The cost of local production encompasses the immediate assembly of rounds, represented by the cost of producing each ammunition type. It also considers the cost of storing ammunition in component form and replacing only the components that have reached their maximum shelf life. The assembly cost represents the expense incurred when ammunition is assembled as needed.

Additionally, the model considers the transition cost involved in transitioning a mothballed facility to a state of readiness for production or shutting down an open facility, or keeping an open facility open, or a closed facility closed. Disposal costs of assembled product are also considered as part of the overall life cycle cost to be borne by Singapore Army. The model offers flexibility for optimization by incorporating penalty costs with elastic variables for both surplus and shortfall of stockpile quantities that permit constraints to be violated at a penalty cost.

Constraints (1) address the inventory levels in each time period. Each constraint considers the balance of flow into, during, and out of a time period. It includes inventory carried over from the previous time period, and additional quantities replenished during the current time period. Furthermore, it also removes the quantities that have been consumed due to training requirements, testing, unserviceability and disposal of aged-out units.

Constraints (2), (3), (4) and (5) ensure that there is sufficient capacity to hold the stockpile inventory at the end of each period. These constraints also take into consideration the storage compatibility between products where only products that are compatible are stored in the same storage facility at the same time. Each product requires a different fraction of capacity of a storage facility; therefore, each product has a reciprocal storage consumption coefficient which represents the burden rate for each ammunition type.

Constraints (6), (7), and (8) ensure that the total shipment of units can satisfy the demand during each period either by utilizing the available holding quantity or assembling components to form product j during period t.

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IV. ANALYSIS

A. IMPLEMENTATION OF THE OPTIMIZATION MODEL

We implemented our model in PYOMO (Bynum et al., 2021; William et al.,2011), utilizing the Gurobi solver (Gurobi Optimization, 2023) to conduct analysis. The model was executed with a dataset consisting of 30 assembled products, 90 components, and 15 production departments using a yearly planning interval over a horizon of 10 years. In total, our model consists of 199,969 variables, out of which 15,188 are binary variables. The model is subject to 61,403 constraints, and we applied an integrality tolerance (i.e., the difference between the best solution found and a bound on how much better a solution might exist) of one percent.

For computation, we employed a personal computer equipped with a 15.0 Gigabyte random access memory and a 3.20 Gigahertz Advanced Micro Devices Ryzen 7 5800H processor. Our computer has a PassMark rating score of 6148 (PassMark Software, 2023). With this setup, the solver took approximately seven seconds. Notably, we achieved a zero percent maximum integer objective gap, which indicates that the solver has found an optimal integer solution.

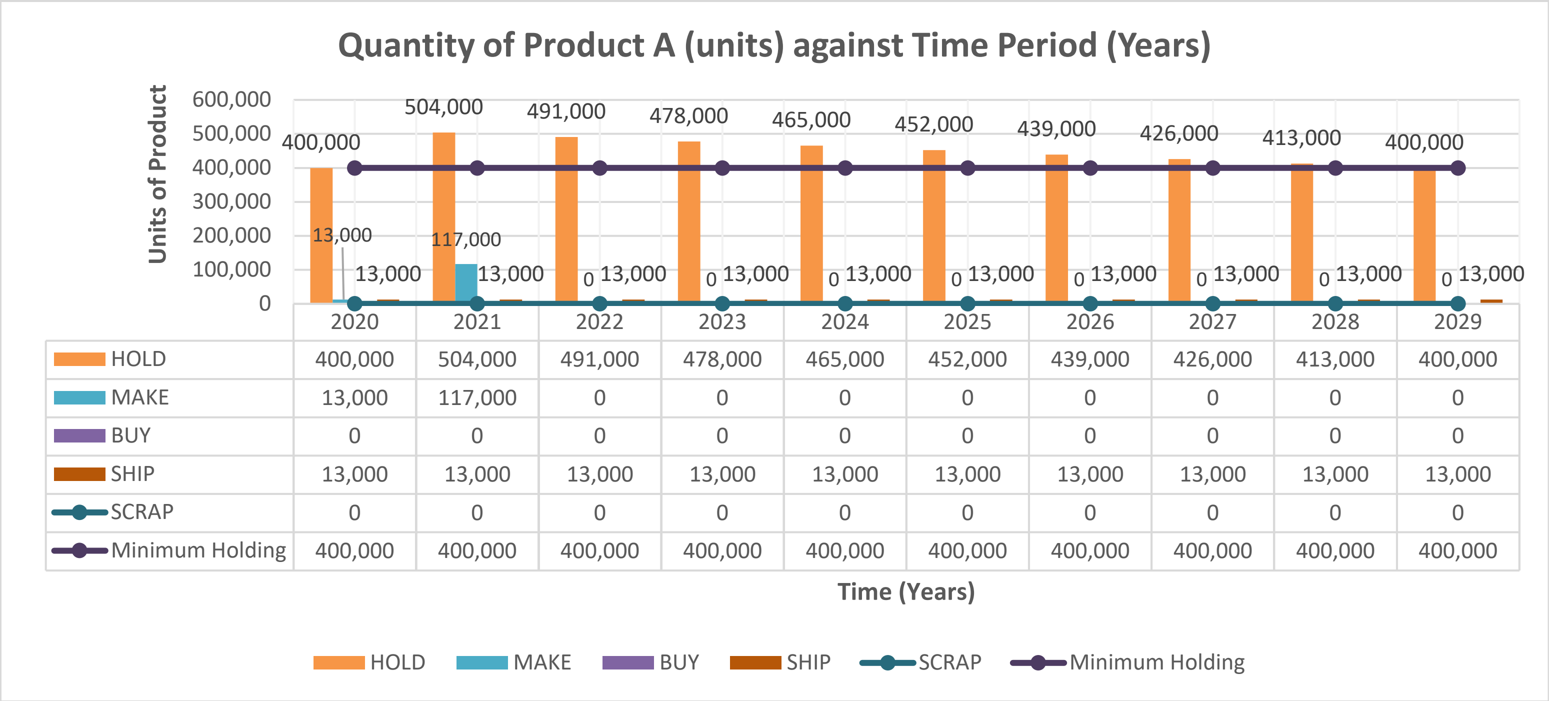
The output from our model provides yearly details for the planning horizon 2020–2029 of the recommended quantities of products manufactured, purchased, disposed of, shipped, assembled, and held in inventory. To facilitate presentation, we directly exported the results to Microsoft EXCEL (Microsoft Corporation, 2018), allowing for both numerical and graphical representations. Product A and B were selected for result analysis and the input data as shown in Table 3.

Table 3. Input Data for Product A and Product B

Input	Product A	Product B
Minimum Holding [Units]	400,000	50,000
Demand [Units]	13,000	0
Minimum Production Rate [Units/time]	0	0
Maximum Production Rate [Units/time]	40,000	50,000
Max age [time periods]	10	5
Cost to MAKE (Assembly Cost) [S$/unit]	S$10	S$80
Component Cost [S$]	S$40	S$50
Cost to BUY [S$/unit]	S$100	S$80
Disposal Cost [S$/unit]	S$20	S$20
Penalty for Shortfall [S$/unit]	S$1,000,000	S$1,000,000
Penalty for Surplus [S$/unit]	S$110	S$110
Transition cost from Closed State to Open State [S$]	S$2,000	S$2,000
Storage Space Required [units]	0.01	0.01

1. Results Analysis

Product A, with a maximum age of 10 years, does not require any units to be disposed of due to its remaining shelf life. We observe from Figure 4 that the output indicates that units consumed to fulfill demand (represented by SHIP) have been replenished through local production (represented by MAKE). This decision is based on the cost-effectiveness of assembling the product and purchasing its components locally, which is less expensive than acquiring the products through an overseas buy. Additionally, our model adheres to the minimum holding quantity requirement, maintaining it at a minimum of 400,000 units each year. Furthermore, our model indicates that bulk production is suggested in the year 2021, when the production rate could satisfy this requirement to meet the minimum holding for the next 10 years.

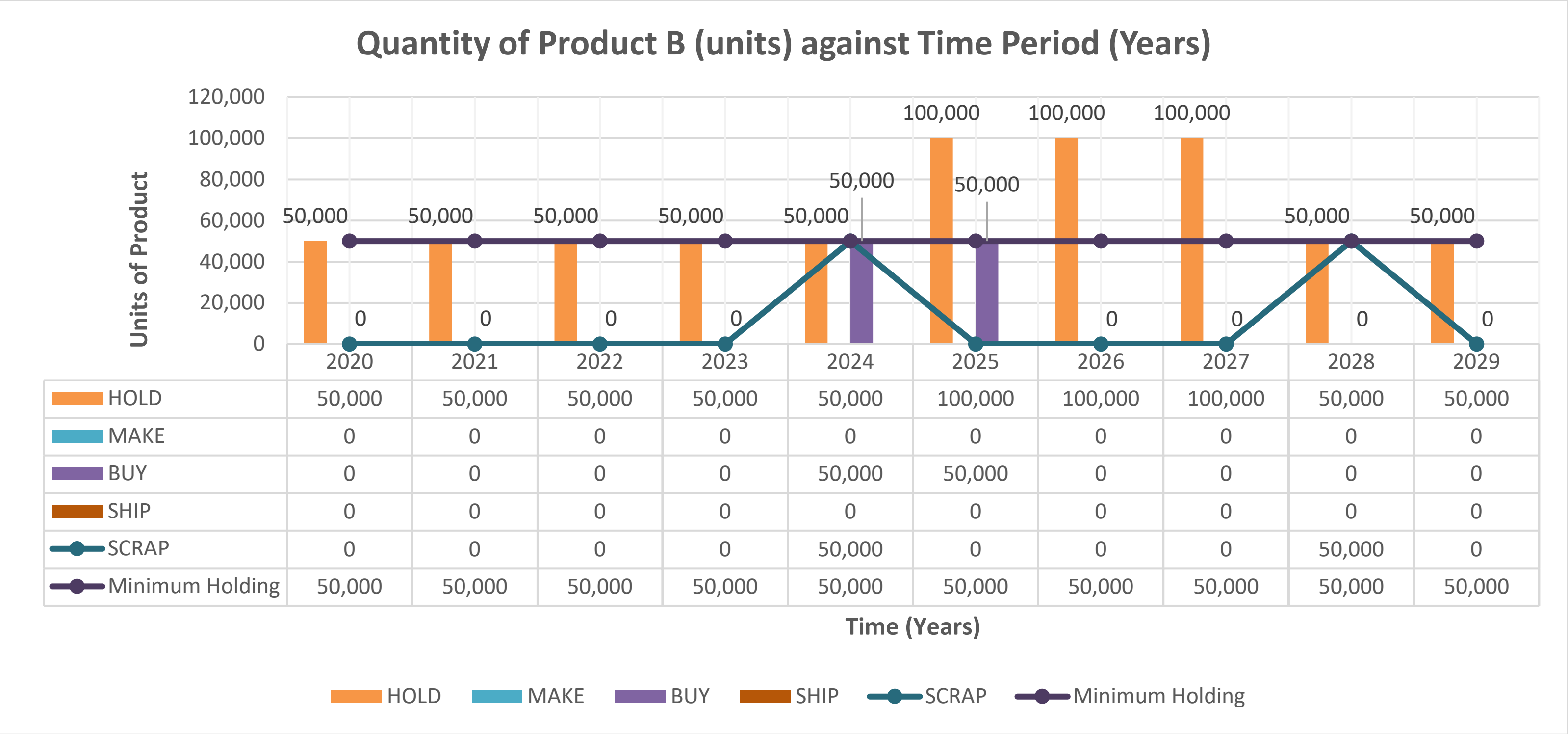


	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HOLD	400,000	504,000	491,000	478,000	465,000	452,000	439,000	426,000	413,000	400,000
MAKE	13,000	117,000	0	0	0	0	0	0	0	0
BUY	0	0	0	0	0	0	0	0	0	0
SHIP	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000
SCRAP	0	0	0	0	0	0	0	0	0	0
Minimum Holding	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000

In each year, aside from fulfilling the holding requirement, we also account for the quantities introduced through MAKE and BUY decisions, as well as the quantities deducted by SHIP and SCRAP activities. For instance, in the year 2021, out of the initial holding quantity of 504,000 units, we generate an additional 117,000 units through production within the same year. This increase augments the previous year's holdings of 400,000 units. However, during the same year, a total of 13,000 units are consumed, resulting in the retention of 504,000 units by year-end.

Figure 4. Result Analysis for Product A

As shown in Figure 5, for product B which has a maximum age of five years and has no shipping requirements, our model opts to purchase instead of produce when the cost of buying is lower than the cost of making. Expired products are disposed of after 5 years and replenished through additional purchases.



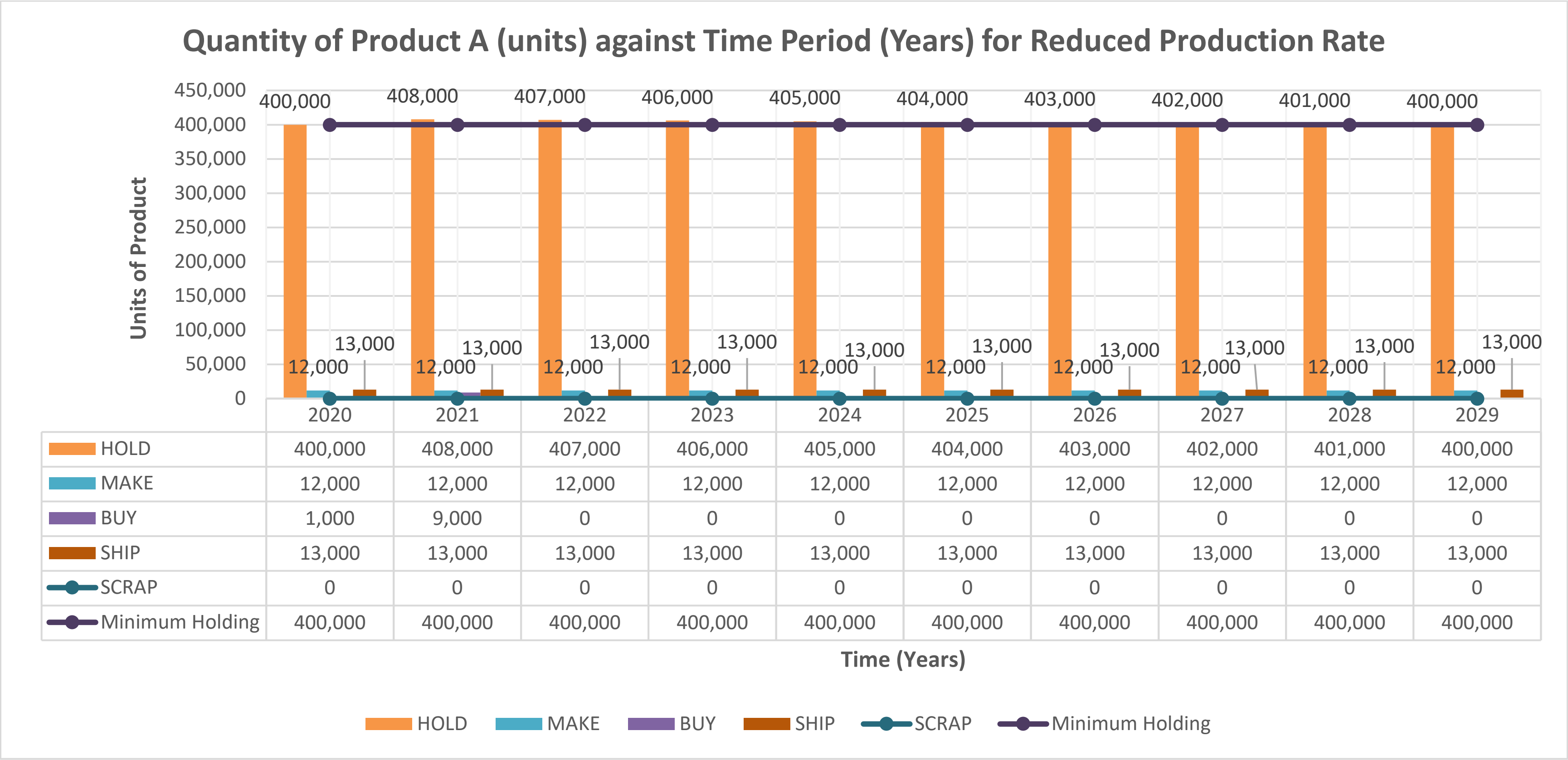
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HOLD	50,000	50,000	50,000	50,000	50,000	100,000	100,000	100,000	50,000	50,000
MAKE	0	0	0	0	0	0	0	0	0	0
BUY	0	0	0	0	50,000	50,000	0	0	0	0
SHIP	0	0	0	0	0	0	0	0	0	0
SCRAP	0	0	0	0	50,000	0	0	0	50,000	0
Minimum Holding	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000

Product B has a shelf life of five years, necessitating disposal at the end of this five-year shelf life. For instance, in the year 2024, 50,000 units have reached its maximum age and thereby require disposal (SCRAP), while concurrently, another 50,000 units are procured to replace the units that have been discarded. This replenishment maintains the inventory at 50,000 units. Moving forward to the year 2025 acquiring an additional 50,000 units fulfills the minimum holding requirement in the upcoming five years, leading up to the subsequent wave of disposal in the year 2028.

Figure 5. Result Analysis for Product B

2. Scenario 1: Reduced Production Rate

For the first scenario, where the maximum production rate of Product A is reduced, our model indicates that the required quantity might not be met through local production to fulfill the minimum holding requirement. Consequently, the model chooses to purchase instead.

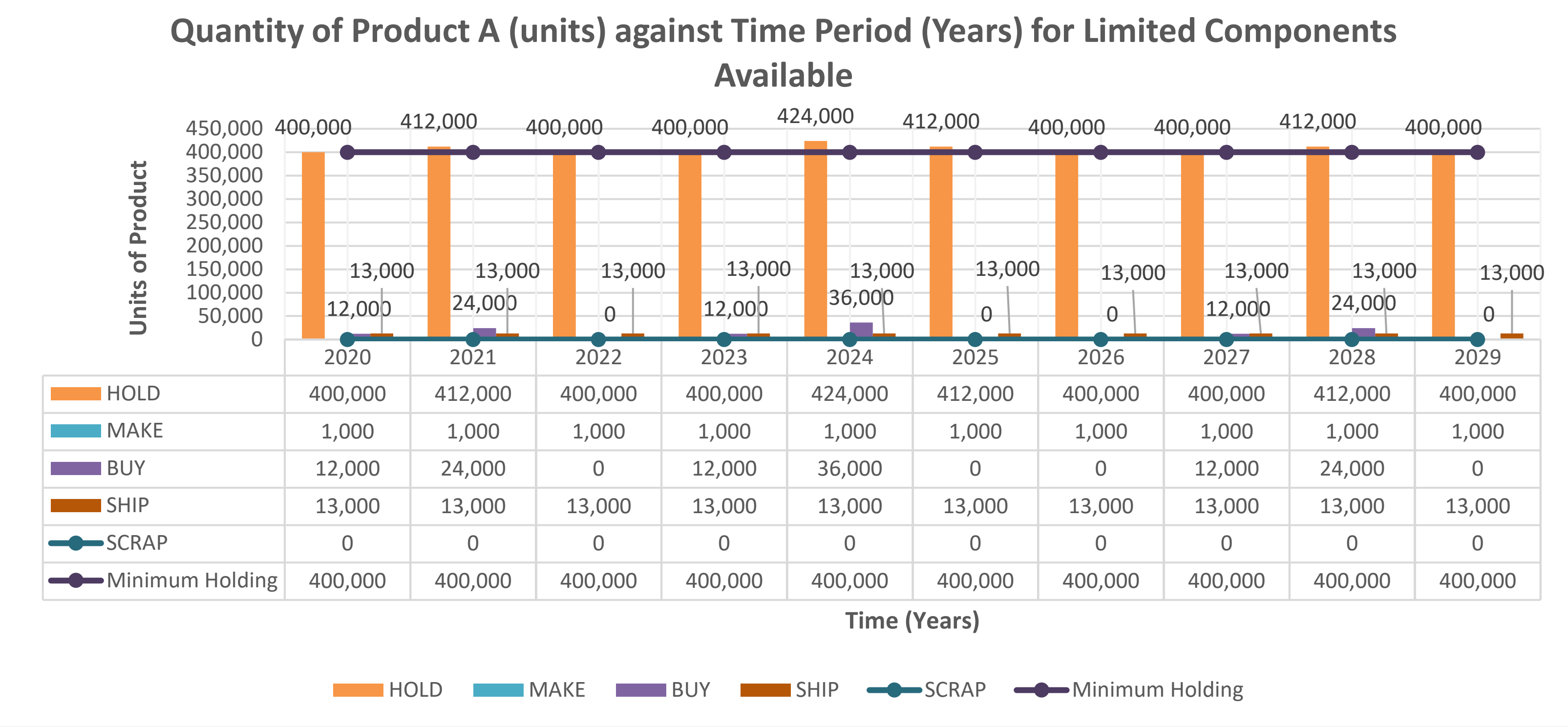


	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HOLD	400,000	408,000	407,000	406,000	405,000	404,000	403,000	402,000	401,000	400,000
MAKE	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000
BUY	1,000	9,000	0	0	0	0	0	0	0	0
SHIP	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000
SCRAP	0	0	0	0	0	0	0	0	0	0
Minimum Holding	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000

Figure 6. Results Analysis for Product A with Reduced Production Rate

3. Scenario 2: Component Availability Influence

In the second scenario, when the availability of components for assembling the product is limited, our model favors purchasing over production. Our model choses to produce locally from the components available and fulfill the remaining requirements through overseas purchase.

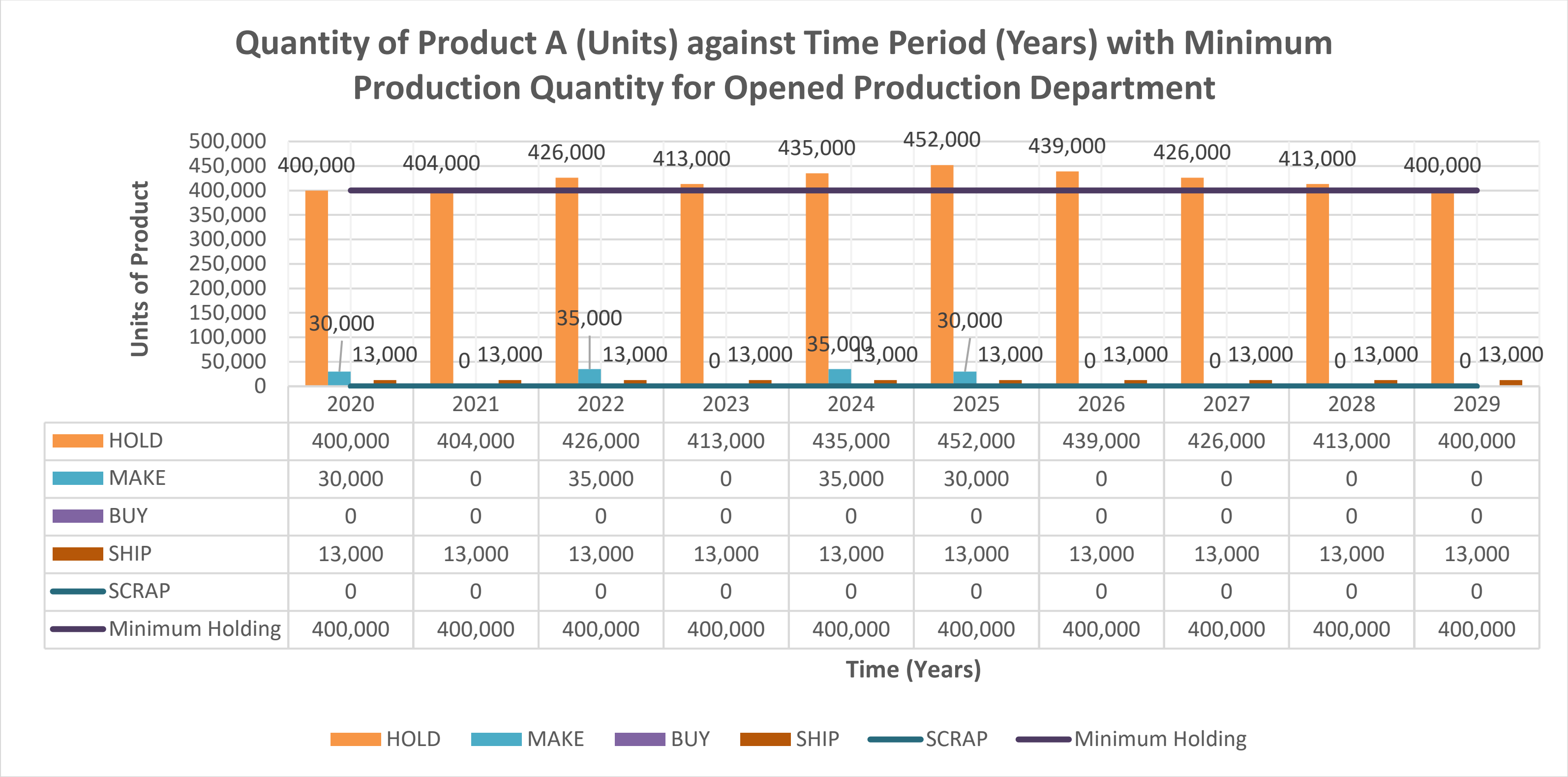


	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HOLD	400,000	412,000	400,000	400,000	424,000	412,000	400,000	400,000	412,000	400,000
MAKE	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
BUY	12,000	24,000	0	12,000	36,000	0	0	12,000	24,000	0
SHIP	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000
SCRAP	0	0	0	0	0	0	0	0	0	0
Minimum Holding	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000

Figure 7. Result Analysis for Product A with Limited Components Available

4. Scenario 3: Sustaining a Production Facility with Minimum Production

In the third scenario, setting a minimum production quantity for each year the production facility is operational leads our model to recommend producing a specific quantity annually to sustain the facility. This strategy distributes production units across multiple years as shown in Figure 8.

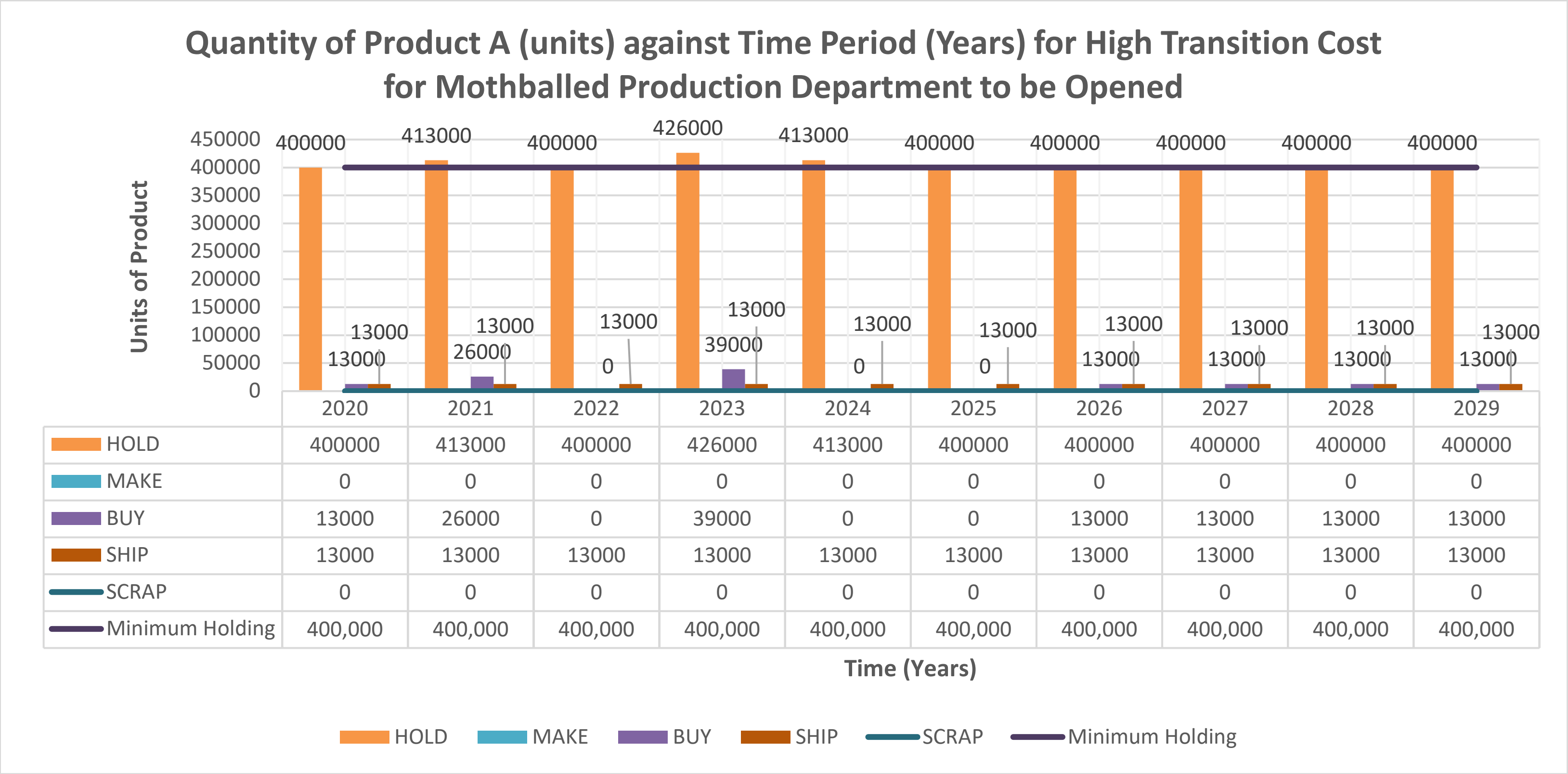


	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HOLD	400,000	404,000	426,000	413,000	435,000	452,000	439,000	426,000	413,000	400,000
MAKE	30,000	0	35,000	0	35,000	30,000	0	0	0	0
BUY	0	0	0	0	0	0	0	0	0	0
SHIP	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000	13,000
SCRAP	0	0	0	0	0	0	0	0	0	0
Minimum Holding	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000

Figure 8. Result Analysis for Product A with Minimum Production Quantity

5. Scenario 4: Increased Transition Cost Given That Production Facility Is Mothballed in 2020

If we assume the production facility starts in a closed state, and the transition cost to open it is high, then opening the facility becomes not cost effective. In such situations, our model chooses to buy from overseas instead of opening a mothballed facility for production as shown in Figure 9.



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HOLD	400000	413000	400000	426000	413000	400000	400000	400000	400000	400000
MAKE	0	0	0	0	0	0	0	0	0	0
BUY	13000	26000	0	39000	0	0	13000	13000	13000	13000
SHIP	13000	13000	13000	13000	13000	13000	13000	13000	13000	13000
SCRAP	0	0	0	0	0	0	0	0	0	0
Minimum Holding	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000

Figure 9. Result Analysis for Product A with High Transition Cost from Mothballed Production Facility

6. Feedback from Personnel Familiar with the Problem and Policies

The analysis of our model was presented via teleconference to the Deputy Commander and Ammunition Engineers of the Singapore Armed Forces Ammunition Command. These representatives, familiar with the management of life cycle costs of the ammunition stockpile, requested assessment of: (1) the use and effectiveness of excess inventory in the face of uncertain demand; and (2) management of a production quantity shortfall. Through our optimization model, we provided a computational tool for these stakeholders.

With respect to (1), holding excess inventory results in additional penalty cost for each unit of production surplus and presents the possibility of insufficient storage space for surplus items. Decision-makers will thus need to determine the penalty cost for each unit of ammunition production surplus. Our optimization model will then be able to compute the increase in life cycle cost involved in the production surplus to allow decision-makers to decide if the surplus is a justifiable cost and within budget. With regards to (2), upon determining the penalty cost for each unit of ammunition production shortfall, our model decides on opting to pay penalties for small-quantity production shortfalls or incurring the high production costs associated with meeting the shortfall.

Our model is able to evaluate various points of view and assess the outcomes of potential policy changes. We look forward to planning excursions and view our model as a "level playing field" on which various stakeholders can express differing policy opinions and evaluate their effects over our planning horizon. The stakeholders are pleased with our model's ability to assess diverse demands, policy changes, and their impacts. They look forward to the adoption of our model.

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V. CONCLUSION

We conclude that the model effectively provides recommendations for optimizing resource utilization and minimizing the overall life cycle cost associated with ammunition management. It demonstrates its capability by recommending optimal strategies such as determining the best timing for both local manufacturing (assembly) and overseas procurement, quantifying the ideal purchase quantities, evaluating the cost-effectiveness of maintaining an active production department for fulfilling product requirements, and even assessing the feasibility and value of reactivating a previously mothballed production department.

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