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“Optimal storage of ammunition and explosive materials in military
warehouses”

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Patras, Greece, “March” “2025”

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“Optimal storage of ammunition and explosive materials in military
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Abstract

In modern times, supply chain efficiency is becoming increasingly important, driving a continuous search for optimization in transportation, inventory, and material placement within warehouses. Thousands of materials are stored daily, including hazardous materials, a subcategory of which comprises explosives and ammunition. This thesis focuses on optimizing the storage of explosives and ammunition across a network of warehouses. Explosives are classified based on three factors: the potential consequences of misuse (e.g. mass explosion), material compatibility groups, and theft risk arising from material attractiveness. Various warehouse types, each with distinct characteristics and restrictions, are considered according to standards outlined in NATO and US manuals. Effective management of these materials is crucial for minimizing risks and ensuring public safety. A theft risk objective function is developed, combining material theft risk and warehouse security levels. This function is minimized using Microsoft Excel's Solver tool to determine optimal storage configurations. Analysis of multiple scenarios revealed four equally optimal solutions, demonstrating that different warehouse-material combinations can yield equivalent risk levels. These solutions consistently favored concentrating materials in the most secure warehouses to minimize overall theft risk, while strategically varying the placement of a key material pair to balance other constraints. This work provides a valuable framework for optimizing the complex storage of hazardous materials, balancing safety, security, and operational constraints within the limitations imposed by material compatibility and warehouse characteristics. The identified optimal solutions offer practical guidance for decision-makers responsible for hazardous material storage.

Keywords

Explosives - Ammunition, Solver, Safe and Secure Storage.

Βελτιστοποίηση αποθήκευσης πυρομαχικών και εκρηκτικών εντός στρατιωτικών μονάδων με εφαρμογή αλγορίθμου βελτιστοποίησης. Σοφία Βασιλειάδου

Περίληψη

Στη σύγχρονη εποχή, η αποδοτικότητα της εφοδιαστικής αλυσίδας αποκτά ολοένα και μεγαλύτερη σημασία, οδηγώντας σε μια συνεχή αναζήτηση για βελτιστοποίηση στις μεταφορές, τα αποθέματα και την τοποθέτηση υλικών εντός των αποθηκών. Χιλιάδες υλικά αποθηκεύονται καθημερινά, συμπεριλαμβανομένων των επικίνδυνων υλικών, μια υποκατηγορία των οποίων περιλαμβάνει εκρηκτικά και πυρομαχικά. Η παρούσα διατριβή επικεντρώνεται στη βελτιστοποίηση της αποθήκευσης εκρηκτικών και πυρομαχικών σε ένα σύνολο αποθηκών. Τα εκρηκτικά ταξινομούνται με βάση τρεις παράγοντες: τις πιθανές συνέπειες από την ακατάλληλη χρήση (π.χ. μαζική έκρηξη), τις ομάδες συμβατότητας υλικών και τον κίνδυνο κλοπής που προκύπτει από την ελκυστικότητα των υλικών. Λαμβάνονται υπόψη διάφοροι τύποι αποθηκών, ο καθένας με ξεχωριστά χαρακτηριστικά και περιορισμούς, σύμφωνα με τα πρότυπα που ορίζονται σε εγχειρίδια του NATO και των ΗΠΑ. Η αποτελεσματική διαχείριση αυτών των υλικών είναι ζωτικής σημασίας για την ελαχιστοποίηση των κινδύνων και τη διασφάλιση της δημόσιας ασφάλειας. Στη συνέχεια, αναπτύσσεται μια αντικειμενική συνάρτηση κινδύνου κλοπής, η οποία συνδυάζει τον κίνδυνο κλοπής των υλικών και τα επίπεδα ασφάλειας των αποθηκών. Η συνάρτηση αυτή ελαχιστοποιείται με τη χρήση του εργαλείου Solver του Microsoft Excel για τον προσδιορισμό των βέλτιστων σεναρίων αποθήκευσης. Η ανάλυση πολλαπλών σεναρίων αποκάλυψε τέσσερις εξίσου βέλτιστες λύσεις, αποδεικνύοντας ότι διαφορετικοί συνδυασμοί αποθηκών-υλικών μπορούν να αποδώσουν ισοδύναμα επίπεδα κινδύνου. Αυτές οι λύσεις ευνοούσαν σταθερά τη συγκέντρωση υλικών στις πιο ασφαλείς αποθήκες για την ελαχιστοποίηση του συνολικού κινδύνου κλοπής, ενώ παράλληλα διαφοροποιήθηκε ένα ζεύγος υλικών για την εξισορρόπηση του περιορισμού συμβατότητας. Αυτή η εργασία παρέχει ένα πολύτιμο πλαίσιο για τη βελτιστοποίηση της σύνθετης αποθήκευσης επικίνδυνων υλικών, εξισορροπώντας την ασφάλεια, τη φύλαξη και τους λειτουργικούς περιορισμούς εντός των ορίων που επιβάλλουν η συμβατότητα των υλικών και τα χαρακτηριστικά των αποθηκών. Οι προσδιορισμένες βέλτιστες λύσεις προσφέρουν πρακτική καθοδήγηση στους υπεύθυνους λήψης αποφάσεων για την αποθήκευση επικίνδυνων υλικών.

Λέξεις – Κλειδιά

Εκρηκτικά – Πυρομαχικά, Βελτιστοποίηση Μοντέλου, Ασφαλής Αποθήκευση.

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List of Abbreviations & Acronyms

AASTP-1	Allied Ammunition Storage and Transport Publication-1
AFMAN 91	Air Force Manual 91-201
AGMs	Above-Ground Magazines
CG	Compatibility Groups
ECM	Earth-Covered Magazines
HDiv	Explosive Hazard Divisions
HEI	High Explosive Incendiary
NEW	Net Explosive Weight
Q-D	Explosives Quantity-Distance
SOPs	Standard Operating Procedures
TNT	Trinitrotoluene
TSA	Temporary Storage Areas
UGM	Underground Magazines
UN number	United Nations number
US DOT	U.S. Department of Transportation

1 Introduction

Globalization has led to increased transportation and storage demands of goods and products. Products vary based on their special treatment during transportation and storage. For example, food products demand specific conservation conditions as they are consumed by people. Also, their arrival time should be much lower than their expiration date. Other products may be sensitive to external stress, such as glass and other fragile products. Moreover, some products may cause harmful consequences when they interact with the environment under non-usual conditions, increasing their transportation and storage risk. They can harm the physical environment (oil leakage), and infrastructure (explosion) and injure people or even lead to death.

Theoretical background

2 Ammunition and explosive materials

In this chapter, we will define what communication materials are, it will become clear what we call ammunition and what explosives. What are the risks arising from possible accidents and their improper use? How they are classified according to American and NATO manuals based on three different criteria.

2.1 Definitions

According to the U.S. Department of Transportation (US DOT) (Erkut et al., 2007) a hazardous material is any substance or material that can cause harm to people, property, or the environment. There are thousands of different hazardous materials in use today. The United Nations classifies hazardous materials into nine groups based on their physical, chemical, and nuclear properties:

- 1) Explosives,
- 2) Gases,
- 3) Flammable Liquid and Combustible Liquid,
- 4) Flammable Solid, Spontaneously Combustible and Dangerous When Wet
- 5) Oxidizer and Organic Peroxide,
- 6) Poison (Toxic) and Poison Inhalation Hazard,
- 7) Radioactive,
- 8) Corrosive,
- 9) Miscellaneous, and the general Dangerous placard.

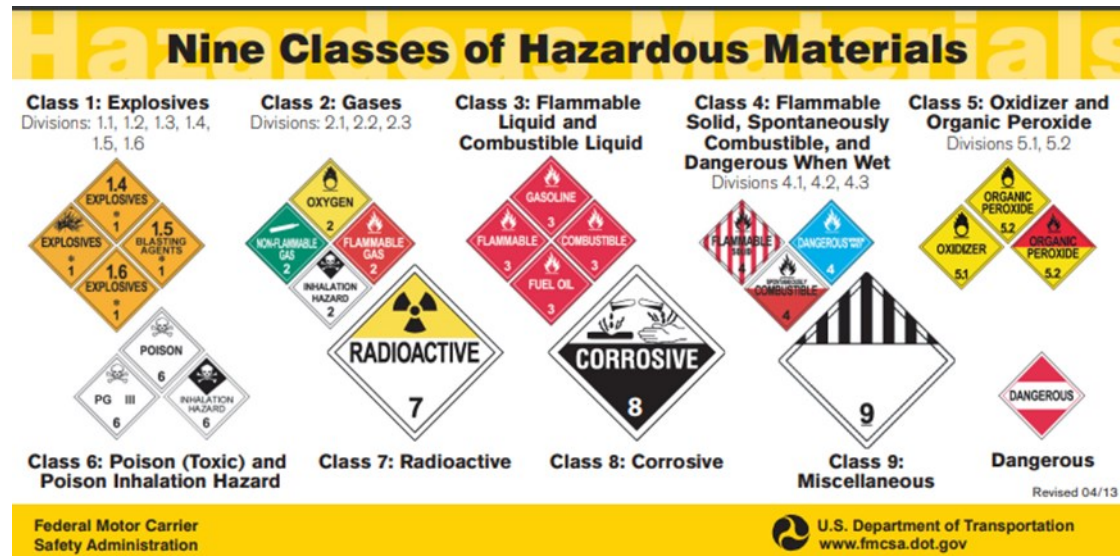


Figure 1. The nine Classes of Hazardous Materials according to Federal Motor Carrier Safety Administration (2013)

According to AFMAN91, there is also an uncontrolled category which includes objects in which there are explosive and hazardous materials, but not to the extent that the criteria are met to assign them to one of the nine categories. The object is assigned to the class that represents the dominant hazard characteristic of the object. Class 1 applies to materials where the explosive hazard prevails over Categories 2 to 9. In this thesis, we will focus only on the first group of hazardous materials, which are explosives and ammunition.

2.1.1 Ammunition

Refers to ammunition designed for use in weapon systems. This includes:

- Projectiles e.g. Bullets, artillery shells, projectiles
- Propellants: these are the materials used to propel projectiles, such as gunpowder or rocket fuel.
- Fuzzing Systems: Mechanisms that create an explosion or ignition.
- Fireworks: Devices that produce effects such as light, smoke or noise for signaling or illumination.

Ammunition can be “explosive” or “non-explosive” (e.g. inert training rounds).

2.1.2 Explosive Materials

Explosive materials are substances or mixtures that produce a rapid release of gas, heat and pressure upon initiation. These materials are categorized in AASTP-1 as:

- Primary Explosives: Highly sensitive items whose use is to initiate larger explosions (e.g., lead azide).

- Secondary Explosives: More stable materials that require significant energy to detonate (e.g., TNT, RDX).
- Propellants: Used in controlled reactions to achieve the propulsion of missiles or rockets.
- Pyrotechnics: Compositions that produce controlled effects such as light, heat, or smoke.

AASTP-1 uses a “Hazard Classification System” to classify munitions and explosives based on their physical and chemical properties, and primarily their reaction behavior under pressure or accidental ignition. There are two classifications which include:

- Explosive Hazard Divisions (HDiv): From HD 1.1 (mass explosion hazard) to HD 1.6 (extremely insensitive explosives).
- Compatibility Groups (CG): Indicates whether certain types of ammunition or explosives can be stored or transported together safely.

2.2 Classification of Explosives and ammunitions

2.2.1 Classification Based on Hazard Divisions

To achieve the safe storage and transport of dangerous goods, the UN International Dangerous Goods Classification System is used. As already mentioned, the system consists of 9 groups (1-9), of which Class 1 includes ammunition and explosives. Class 1 is divided into six divisions, which indicate the main type of hazard expected in the event of an accident:

- Division 1.1: Substances and articles presenting a mass explosion hazard
- Division 1.2: Substances and articles presenting a projection hazard but not a mass explosion hazard
- Division 1.3: Substances and articles presenting a fire hazard and either a small explosion hazard or a small projection hazard or both, but not a mass explosion hazard
- Division 1.4: Substances and articles presenting no meaning hazard
- Division 1.5: Very insensitive substances presenting a mass explosion hazard
- Division 1.6: Extremely insensitive articles presenting no mass explosion hazard.

The above classification is made following AASTP-1. This classification indicates the guidelines and safety principles for the hazard classification of military ammunition and explosives.

Ammunition and explosives are considered compatible if they can be stored together without significantly increasing either the probability of an accident or, for a given quantity, the magnitude of the consequences of a possible accident. Ammunition and explosives should not be stored together with other goods that may damage them, for example, highly flammable materials, acids, and corrosives. The safety of ammunition and explosives in storage would be optimal if each type were kept separately. However, a proper balance of the interests of safety against various factors may require the mixing of several types of ammunition and explosives, e.g. due to a lack of dances. The principles of mixing compatibility groups differ according to the conditions of storage and transport (AASTP-3).

2.2.2 Classification according to Compatibility Groups

Ammunition and explosives are officially grouped into thirteen compatibility groups: A through H, J, K, L, N, and S according to AASTP-1. Group I is omitted to avoid possible confusion between the letter "I" and the Roman numeral "I".

- **Group A:** Primary explosive substances.
- **Group B:** Articles with a primary explosive substance, lacking two or more effective protective features.
- **Group C:** Propellant explosives or other deflagrating substances, or articles containing such substances.
- **Group D:** Secondary detonating explosives, black powder, or articles containing secondary detonating substances, all without initiation means or a propelling charge. This also includes articles with primary explosive substances that have two or more effective protective features.
- **Group E:** Articles with secondary detonating explosives, equipped with a propelling charge but no initiation means. This excludes items containing flammable liquids, gels, or hypergolic liquids.
- **Group F:** Articles with secondary detonating explosives that have built-in initiation means, with or without a propelling charge, excluding those containing flammable liquids, gels, or hypergolic liquids.
- **Group G:** Pyrotechnic substances, or articles containing pyrotechnic substances, or those combining explosives with illuminating, incendiary, tear-producing, or smoke-producing substances. This excludes water-activated items or those with white phosphorus, phosphides, pyrophoric substances, flammable liquids, gels, or hypergolic liquids.
- **Group H:** Articles containing both explosive substances and white phosphorus.
- **Group J:** Articles containing both explosive substances and flammable liquids or gels.
- **Group K:** Articles containing both explosive substances and toxic chemical agents.
- **Group L:** Explosive substances or articles posing unique risks, such as water activation, hypergolic liquids, phosphides, or pyrophoric substances, requiring isolation for safety.
- **Group N:** Articles containing only extremely insensitive substances.
- **Group S:** Substances or articles designed or packaged to confine hazardous effects within the package during accidental activation, unless fire compromises the package. In such cases, blast and projection effects are minimized to avoid hindering fire-fighting or emergency response efforts in the area.

Table 1. Compatibility Groups

Compatibility Group	A	B	C	D	E	F	G	H	J	K	L	N	S
A	X												X
B		X											X
C			X	X	X								X
D			X	X	X								X
E			X	X	X								X
F						X							X
G							X						X
H								X					X
J									X				X
K										X			
L													
N													
S		X	X	X	X	X	X	X	X				X

Table 1 is a simplified version of the compatible groups reported at AASTP-1 and AASTP-5. Specifically, in this thesis, only the main compatibility groups are considered and not all sub-categories, since they constitute very specific and rarely observed situations. In Table 1 compatible groups are marked with an “X”.

2.2.3 Classification based on Security Risk due to Attractiveness

The distinction presented by both AASTP-1 and AASTP-5 is also very important to address the importance of security measures based on the attractiveness of ammunition in terms of its theft or misuse. Ammunition that is considered “attractive” —usually small arms ammunition, explosives, or materials that are portable and have a high potential for illicit use—is subject to more stringent security requirements. Materials can be classified into the following categories based on their attractiveness:

- **High-risk ammunition:** In this category are small, portable, and easily concealed items, such as small arms ammunition, detonators, and plastic explosives. These items are often attractive to criminals, insurgents, or terrorist groups due to their utility and ease of transport.
- **Medium-risk ammunition:** This category includes items that are less portable or require the use of specific equipment, such as larger caliber ammunition or certain types of fire extinguishers.
- **Low-risk ammunition:** This category includes ammunition that is bulky, difficult to transport, or requires significant expertise or infrastructure for effective use.

3 Ammunition warehouses

3.1 Types of Storage for Ammunition

- **Earth-Covered Magazines (ECM):** They are reinforced storage facilities covered with soil to provide physical insulation and additional protection from external threats e.g. explosion or fire. Designed for the storage of sensitive or large quantities of ammunition. Their key features are blast resistance, temperature regulation and separation distance requirements to mitigate the effects of explosives.
- **Above-Ground Magazines (AGMs):** They are self-contained structures constructed above ground, constructed with reinforced materials such as concrete or steel. They are used for smaller quantities of ammunition or items that do not require additional protection with earthworks. They are often easier to access than ECMs but require strong security protocols.
- **Underground Magazines:** They are storage facilities built below ground level, often in natural or excavated caves or tunnels or bunkers. Their purpose is to provide a high level of protection against external threats, especially for critical or highly sensitive munitions. Their basic characteristics are that they maintain extremely stable temperatures and security. However, they have higher construction and maintenance costs.
- **Temporary Storage Areas (TSA):** Short-term storage facilities are often created in operational or field environments. Intended to support immediate operational requirements or logistics in remote areas. Typically less permanent structures such as containers or prefabricated units, with an emphasis on mobility.
- **Ready-to-use stores:** Storage areas near operational locations where ammunition is stored for immediate or near-immediate use. Providing rapid access to ammunition during ongoing operations. Providing greater proximity to the operational area, typically with smaller inventories and tighter handling controls.
- **Inert storage facilities:** These are specialized facilities for the storage of non-explosive ammunition components, such as training cartridges. They reduce the risk of accidental ignitions or explosion. Inert storage facilities focus on safety and separation from live ammunition.
- **Break-bulk or Transit Warehouses:** These are warehouses used for temporary storage during transport or redistribution. The purpose of Break-Bulk or Transit warehouses is to facilitate efficient supply and minimize handling risks during transportation. Their characteristic is the emphasis on accessibility and efficiency.

Each type of warehouse follows specific design standards, security protocols, and environmental considerations to ensure compliance with NATO standards and to mitigate the risks associated with the storage of explosive materials (AASTP-1).

3.2 Storage Safety and Explosive Safety Principles

The principles that ensure safety, security, and efficiency in the handling and storage of ammunition and explosives. The following are the basic requirements and principles according to AASTP-1 and AASTP-5:

1. Safety Principles:

- a. Explosives Quantity-Distance (Q-D) Criteria: Minimum distances should be maintained between ammunition storage locations and residential areas to minimize the risk of accidental explosions. There are Q-D tables that give safe distances for residential buildings, public transport routes, and operational areas.
- b. Explosives Segregation: Incompatible explosives should be stored separately to prevent accidental detonation. By using appropriate hazard classification and compatibility group (HC/CG) designations.
- c. Ventilation and Environmental Controls: There must be adequate ventilation in the storage facilities so that heat or fumes do not accumulate. You should also control the temperature and humidity to prevent the deterioration of the ammunition.
- d. Fire safety measures: Fire extinguishing materials, fire-resistant building materials and emergency fire extinguishing equipment are essential. It is also necessary to establish fire protection protocols and ensure that personnel are trained in fire safety.

2. Security requirements

- a. Access control: Strict access control measures are required to limit entry to authorized personnel only. The presence of fencing, guardrails, surveillance systems and alarms is necessary.
- b. Physical Security of Warehouses: Storage areas are intended to be reinforced structures, with secure locks and mechanisms that cannot be tampered with. In some cases, the existence of continuous monitoring and periodic inspections is essential. The above measures are necessarily proportional to the materials stored within the warehouses.
- c. Protection from external threats: The assessment of risks from theft, sabotage or terrorist attacks. The incorporation of security measures such as barriers, motion sensors and emergency plans for emergency situations.

3. Storage Design and Infrastructure

- a. Types of storage facilities: Use earth-covered magazines (ECM), above-ground magazines (AGM) or underground magazines (UGM) depending on the nature

and volume of the ammunition. Design facilities to withstand internal explosions and external impacts.

- b. Separation and protection zones: You should provide adequate space between storage facilities to reduce the risk of chain reactions in the event of an explosion. Implement zoning plans for administrative areas, storage areas and access routes.
- c. Roads and transportation: It is necessary to have well-maintained internal and external access routes to facilitate safe transportation. Separate explosives transport routes from public areas when possible.

4. Operation and Maintenance Instructions

- a. Inspection and Maintenance: Provide regular inspection of ammunition for signs of deterioration, corrosion or instability. You should conduct periodic maintenance of storage facilities to ensure structural integrity and safety.
- b. Handling and Loading/Unloading Procedures: Follow standard operating procedures (SOPs) for moving and handling ammunition. Use appropriate tools, equipment and training to prevent accidents.
- c. Inventory Management: Maintaining accurate inventory records, including lot numbers and expiration dates, is essential. Existence of stockpiles to ensure proper handling of ammunition with a limited shelf life.

5. Environmental and Legal Compliance

- a. Environmental Protection: In addition, it is important to mitigate environmental impacts by limiting spills, managing waste, and preventing contamination. You should monitor surrounding ecosystems for signs of pollution or damage caused by ammunition storage.
- b. Compliance with National and NATO Regulations: Compliance with national and NATO standards, including applicable environmental, health and safety laws.

6. Emergency and Contingency Planning

- a. Emergency Response Plans: It is of utmost importance to develop and review plans for explosions, fires, or other emergencies. As well as training personnel in first aid, evacuation, and incident management procedures.
- b. Risk assessment and mitigation: Conduct regular risk assessments to identify and address potential risks. Implementing mitigation measures such as redundancy in storage areas and alternative supply routes.

- c. Incident investigation and reporting: Documenting and analyzing any safety or security incidents to prevent recurrence. Another way to achieve this is by sharing findings and lessons learned with NATO and national stakeholders.

Both AASTP-1 and AASTP-5 emphasize a proactive approach to risk management, ensuring that ammunition storage facilities remain safe, secure, and operationally effective.

3.3 Warehouse safety measures based on material attractiveness

The following is a detailed analysis of specific security measures for attractive, moderately attractive, and unattractive ammunition stores, as described by U.S. Department of Defense (2020) and U.S. Army (2019), tailored to address the risks associated with potential theft or misuse of each category:

1. Highly Attractive Ammunition Security Measures:

- a. Access Control: This is achieved through strict access control protocols, including biometric authentication, security badges, and a two-person rule (double check) for access. Additionally, you should maintain a record of all personnel with access to the storage area.
- b. Physical Security: Stored entirely in reinforced structures, such as underground magazines (ECMs) or above-ground magazines (AGMs) with tamper-resistant locking systems. Doors and windows should be blast-resistant where provided.
- c. Surveillance: Continuous video surveillance with recording capabilities is required, and intrusion detection systems such as motion sensors and alarms are linked to a central monitoring station.
- d. Fencing and barriers: To prevent unauthorized access, double perimeter fencing with clear zones between the fences should be installed. Anti-climb measures and barriers should also be installed around the storage facility.
- e. Patrolling and security: Regular patrols by armed security personnel are required. Presence of either observation posts or guard towers where necessary.
- f. Transportation: Use of escorted vehicles and GPS tracking for the transport of high value items. Security seals applied to shipping containers.

- g. Inventory and controls: Daily inventory checks are required. It is also necessary to maintain detailed records of all transactions and conduct frequent checks.

2. Medium-Attractive Ammunition Security Measures:

- a. Access Control: Access should be controlled by security signs or PIN-based systems. You should also keep a log of personnel entering the area.
- b. Physical Security: The materials should be stored in secure above-ground magazines (AGMs) or in well-maintained, reinforced facilities. The locks used should have tamper-resistant features. Blast-resistant measures may not be mandatory.
- c. Surveillance: Periodic monitoring using security cameras and alarms for unauthorized access is required. However, 24/7 monitoring may not be required in low-risk areas.
- d. Fencing and Barriers: Single perimeter fencing with clear zones and controlled entry points is essential. You should regularly check fences for breaches or damage.
- e. Patrolling and Guarding: Patrols are considered routine patrols and armed personnel are not required. Guards may be posted at facility entrances during business hours.
- f. Transportation: Transportation security protocols, including monitoring systems, are expected, but escorts may not be required.
- g. Inventory and Audits: Weekly or bi-weekly inventory checks are required, as well as maintaining a record of transactions.

3. Unattractive Ammunition Security Measures:

- a. Access Control: There are minimal access restrictions for this category of materials, such as keyed locks or basic access control systems. A logbook is recommended but not always mandatory.
- b. Physical Security: Storage can be in basic facilities, such as standard warehouses or shipping containers with basic locks. No special strengthening or blast-proofing measures are required.

- c. Surveillance: Basic surveillance is necessary, such as periodic checks by security personnel. Continuous video surveillance or alarms are not required.
- d. Fencing and Barriers: Fencing for this category of materials is optional but recommended to prevent occasional unauthorized access. Signs indicating restricted access may be sufficient.
- e. Patrol and guarding: Occasional patrols or security inspections during off-hours are useful.
- f. Transportation: Security measures are covered by standard logistics protocols without additional security measures.
- g. Inventory and audits: Monthly or quarterly inventory checks are sufficient as well as maintaining basic records for accountability.

Table 2. Comparison of attractiveness

Comparison Table						
Category	Access Control	Physical Security	Surveillance	Fencing	Patrolling	Inventory
High-Attractiveness	Biometric, dual control	Blast-resistant reinforced	24/7 video, alarms, sensors	Double-perimeter, anti-climb	Armed patrols, frequent	Daily, detailed audits
Medium-Attractiveness	Badge/PIN, logbook	Reinforced, tamper-evident	Periodic video, alarms	Single-perimeter	Routine patrols	Weekly, periodic audits
Non-Attractiveness	Basic lock/key, optional	Standard warehouse/container	Occasional checks, optional	Optional	Occasional checks	Monthly/quarterly

Table 2 summarizes all the required safety measures, categorized by material attractiveness. This table facilitates the understanding and comparison of these measures. It is understood that AASTP-1 and AASTP-5 place great emphasis on risk-based security design to ensure proportionate security measures. The more attractive the munitions, the more stringent the security requirements for access control, facility design, monitoring, and stockpile management.

4 Methodology

4.1 The Problem

The scope of the thesis is to store explosives and ammunition in several storages. The storage should be optimized based on the risk of thieving. To do this, based on the attractiveness of each material, an objective function is created which we want to minimize. The materials were selected as representative of the general categories of explosives and ammunition that are thoroughly presented in section 4.3. For simplicity, the storage was selected to have the same volume capacity and explosive material capacity. Specifically, the type of storage is Earth-Covered Magazines (ECM), as discussed in section 3.1.

4.2 Solver

Solver is a powerful optimization ad-on of Microsoft Excel used to perform advanced data analysis and solve complex problems involving constraints and variables. It uses iterative algorithms to find optimal solutions for linear and nonlinear models. Solver adjusts input variables to achieve the desired result. It is particularly useful for scenarios that require decision-making, such as minimizing costs, maximizing profits, or balancing resource allocation, while adhering to specific constraints. Solver allows users to specify an objective function, decision variables, and constraints, making it highly versatile for a variety of fields, including business, engineering, and scientific research (Briones et al, 2020) (Simplilearn, 2024).

Solver is used to systematically adjust decision variables within specified limits to find the most efficient or effective solution to a problem. When using Solver, the user specifies a goal, such as minimizing a cost function or maximizing a revenue function, and specifies constraints that must be satisfied. These constraints can be equalities, inequalities, or bounds on variables. Solver then uses methods such as the Simplex algorithm for linear programming, the GRG Nonlinear method for nonlinear problems, or the Evolutionary algorithm for more complex scenarios to achieve an optimal or near-optimal solution.

4.3 Materials

In the context of the thesis, seven materials were selected as representative of a wide range of ammunition and explosives. The scope was to provide an informative way of optimal storage of such materials, meaning that the reader can easily adapt current categorization to their needs. The selected materials are:

Material 1: Rocket Engine URM-1

The URM-1 rocket motor is mounted inside the VS-1 BRI ejection seat, used in aircraft such as the Czech L-39 Albatross. It is designed to propel the seat in case of emergent pilot ejection. Its main function is to raise the seat from ground level ("Zero-Zero") to a sufficient height for safe parachute deployment. The length of the motor is 410 mm, and its diameter is 136 mm, it weighs about 10 kg and operates effectively in a temperature range from -60°C to +60°C. The propellant charge weighs about 2,580 kg, with an additional charge of 42 g. The URM-1's

lifespan is nine years in storage and eight years or 1,600 flight hours when installed on an aircraft. More information about VS-1 BRI can be found at Tara Aerospace, 2025.



Figure 2. Rocket Engine URM-1 «(source: Tara Aerospace (2025))»

Material 2: Percussion Detonator UD-M76 P1

The UD-M76 P1 percussion detonator is a device used to initiate the detonation of an explosive charge by mechanical impact or percussion. It consists of components that ensure the reliable transfer of energy from mechanical action to the explosive material. The UD-M76 P1 is a specific type of detonator designed as a component of the UBR-M75P1 fuse assembly. It includes the cap, the delay device, the initial transit powder, and the detonator powder, all working together to initiate the explosive sequence. The UD-M76P1 is 70 mm long with a diameter of 12 mm, weighs 13 grams, and has an M10x0.75 thread. It operates in a temperature range of -10°C to +50°C and has a delay time of 3 to 4.4 seconds. It is classified as 1.4B according to the classifications mentioned in 2.2.1 and 2.2.2. It is usually packed in quantities of 100 per carton, with larger shipments stored in metal and wooden boxes. Its shelf life is 12 months in storage but extended to 10 years when incorporated into a grenade and stored under recommended conditions (Tara Aerospace, 2025).



Figure 3. Percussion Detonator UD-M76 P1 a «(source: Tara Aerospace (2025))»

Material 3: Infrared Decoy Flare MJU-7A/B

The MJU-7A/B is an infrared decoy flare, designed to protect aircraft from heat-seeking missiles by emitting infrared radiation. The MJU-7A/B imitates the heat of the aircraft engine,

thus deflecting incoming threats. The manufacturer of this flare is TARA Aerospace. The length of the flare is 205 mm. The body dimensions are 25 x 52 mm² and weigh up to 370 grams. It is launched using a BBU-36/B pulse cartridge. The standard packaging includes 88 pieces per plywood box, 700 x 365 x 270 mm³ dimensions, and a gross weight of 40 kg. The storage life of the flares is 9 years, and the installation period is 1 year (*Tara Aerospace, 2025.*).



Figure 4. Infrared Decoy Flare MJU-7A/B «(source: Tara Aerospace (2025))»

Material 4: TNT 1LB

TNT, or trinitrotoluene, is widely used as a military and industrial explosive, preferred for its relative stability and ease of handling. A 1-pound block of TNT is a standard unit used in a variety of applications, including demolition, and as a reference point for measuring explosive energy. Its compact form allows for precise placement and controlled detonation, making it suitable for tasks such as breaching barriers or demolishing structures. TNT's chemical composition provides a balance between explosive power and safety as it is less sensitive to vibration and friction than other high explosives. This feature reduces the risk of accidental explosions during handling and transport. The energy released by a 1-pound charge of TNT is often used as a benchmark in explosives engineering to evaluate the relative strength of other explosives or to estimate the effects of detonation in various scenarios (U.S. Environmental Protection Agency, 2014).



Figure 5. TNT 1LB, Militaria «(source: Plaza (2025))»

Material 5: Cartridge 9x19 mm

The 9×19 mm cartridge, also known as the 9 mm Luger or 9 mm Parabellum, is one of the most widely used pistol and submachine gun calibers in the world. Developed in 1901 by

Georg Luger, it was designed to balance performance and practicality, offering manageable recoil, reliable feed and effective terminal ballistics. The cartridge features a bullet diameter of 9.01 mm and a case length of 19.15 mm, with a variety of bullet weights and designs ranging from full metal jacket (FMJ) to hollow point (HP) for different applications. It is preferred by military, law enforcement, and civilian shooters because it offers versatility, availability, and consistent performance. The 9×19 mm cartridge is the most popular choice for self-defense, competitive shooting, and service use due to its compatibility with a wide range of firearms (Outdoor Limited, n.d.).



Figure 6. Cartridge 9x19 mm «(source: Lentzis (2025))»

Material 6: Rocket Motor MK92 MOD0

Rocket motor MK92 MOD0 is a propulsion device used in various applications, including military aircraft systems. The purpose of a rocket engine is to create thrust by rapidly expelling gases produced by the combustion of solid or liquid propellants. Unlike traditional jet engines, rocket engines do not require atmospheric air to operate. This property makes them ideal for applications where compact, high-energy propulsion is required, such as rocket systems or ejection seats. They are primarily used in aircraft for emergency ejection systems to safely propel pilots out of the aircraft during an emergency. The MK92 rocket engine is specifically designed for use with the Martin-Baker MK H7 ejection seat, which is installed on aircraft such as the F-4 Phantom. This under-seat rocket motor provides additional thrust to ensure the pilot is ejected at a safe distance from the aircraft in an emergency. The engine weighs about 27 kg, which includes about 6.5 kg of solid propellant. It is initiated by a gas system and plays a critical role in the performance of the ejection seat, enhancing the chances of survival for pilots during high-speed or low-altitude ejections (WBParts, n.d.).



Figure 7. Rocket Motor MK92 MOD0 «(source: WorthPoint (2024))»

Material 7: 30 mm High Explosive Incendiary (HEI)

The 30 mm incendiary (HEI) round is used to combat unarmored and lightly armored ground vehicles, enemy manpower, and air targets. The rounds are compatible with 30 mm automatic guns installed on aircraft for example on Su-25, Su-27, Yak-141, MiG-29 and Mi-24P helicopters, and others. The rounds provide a high explosive and incendiary effect approximately 30 cm behind the point of impact inside the target. The ammunition is suitable for both single-shot and automatic fire modes, with options for slow and fast rates of fire. The round's velocity is approximately 890 meters per second and has an effective range of up to 4,000 meters against ground targets. The projectile weighs approximately 390 g, including an explosive charge of approximately 48.5 g (Arsenal BG, n.d.) (Directorate of Ordnance, DDPDOO, n.d.).



Figure 8 . 30 mm High Explosive Incendiary (HEI) «(source: Arsenal Defense (2025))»

4.4 Constant parameters

Table of risk

The materials are classified based on their attractiveness as we presented in 2.2.3. The materials that have been selected were characterized according to this classification with numbers from 1 to 3, with 1 representing the most unattractive materials and 3 the most attractive ones. The available warehouses were also classified according to their security level. Level 1 warehouses have the strictest security measures, while level 3 corresponds to warehouses with the less strict security measures (e.g. non-continuous monitoring and alarms). Table 3 presents the products between the risk of theft due to material attractiveness and the level of security of each warehouse. The final product indicates the total risk of storing material in each warehouse.

Table 3. Risk of attractiveness per material and warehouse.

Attractiveness of materials	Risk							Safety of warehouses
	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	
	2	1	1	3	3	2	2	
Warehouse 1	6	3	3	9	9	6	6	3
Warehouse 2	4	2	2	6	6	4	4	2
Warehouse 3	4	2	2	6	6	4	4	2
Warehouse 4	2	1	1	3	3	2	2	1
Warehouse 5	2	1	1	3	3	2	2	1

Packaging units

Table 4. Packaging Units

Packaging Units						
Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7
2	900	88	1	50	1	54

Table 4 presents the total quantity of each material (explosives and ammunitions) that has to be stored in the warehouses.

Net explosive weights

Table 5 presents the net explosive weight of material both per unit and per package. To gain the second row of Table 5 the quantities of its first row were multiplied with the quantities of Table 4.

Table 5. Net Explosive Weight (NEW)

Net Explosive Weight (NEW)							
	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7
Unit NEW	5.7804	0.005	0.57541	1	0.003	6.5	0.107
Package NEW	11.5608	4.5	50.63608	1	0.15	6.5	5.778

Packaging Dimensions

Table 6. Area of packages for each material

Packaging Area (m ²)						
Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7
0.2627	0.047736	0.2555	0.00851	0.00635	0.0374625	0.34825

Table 6 shows the area each package occupies. This area is the product of the length and the width of each package.

Quantities of materials for storage

Table 7 shows the quantities that must be stored in specific warehouses.

Table 7. Quantities of materials for storage

Quantities of materials for storage							
	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7
Quantity of Materials	100	2000	5000	900	900000	400	120

Compatibility groups

Table 8 classifies the materials to be stored based on the compatibility criterion during their storage, as explained in the section Classification according to Compatibility Groups 2.2.2.

Table 8. Compatibility Groups of each material

Compatibility Groups						
Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7
C	B	G	D	S	C	E

4.5 Decision Variables

To run the Solver, Table 9 was created. The solver can change the values in this table until it finds the optimal solution. The table includes the decision variables, which in this case represent the quantities of each material that will be stored in each of the available warehouses.

Table 9. Decision Variables

	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7
Warehouse 1	X	X	X	X	X	X	X
Warehouse 2	X	X	X	X	X	X	X
Warehouse 3	X	X	X	X	X	X	X
Warehouse 4	X	X	X	X	X	X	X
Warehouse 5	X	X	X	X	X	X	X

4.6 Objective Function

The purpose of the thesis is to minimize the risk of theft of stored materials. Therefore, the objective function calculates the specific risk by adding up the individual risks created by storing each material in a specific warehouse. To calculate the objective function in Excel, the product of each element in Table 3 with its corresponding element in Table 9 was summed (see Eq. 1). The first term of the objective function concerns the double summation of the product quantities for each material and warehouse with the corresponding risk of attractiveness. The second term of the objective function is a penalty term that prevents the co-storage of incompatible materials. Within this context, λ represents a large penalty factor. $Q_{w,m'}$ corresponds to the quantity of any incompatible material with material m stored in warehouse w . This complex term does not have any physical meaning; rather, it is a numerical method to drive the objective function (OF) to an exhaustive exploration of solutions, making the co-storage of incompatible materials extremely costly.

$$OF = \sum_{m=1}^M \left(\sum_{w=1}^W Q_{w,m} \cdot RoA_{w,m} \right) + \lambda \cdot \sum_{w=1}^W \left(\sum_{m=1}^M \left(Q_{w,m} \sum_{m' \in I(m)} Q_{w,m'} \right) \right) \quad \text{Eq. 1}$$

Where:

OF: Objective Function

M : Total kinds of materials in this thesis this number is seven

W : Total number of warehouses in this thesis this number is five

$Q_{w,m}$: Quantity of material m in warehouse w (decision variable) (Table 9)

RoA: Risk of Attractiveness (Table 3)

λ : large penalty factor

$I(m')$: Set of all materials with material m .

4.7 Restrictions

Storage quantities

This is a balancing constraint expressing the number of materials that must be stored within the available storage spaces. These quantities are shown in Table 7. The sum of the values that the solver will give in Table 9 must be equal to the quantities to be stored (Table 7). This restriction can mathematically be expressed in Eq. 2.

$$\sum_{w=1}^W Q_{w,m} = TQ_m, \text{ for } m = 1, 2, \dots, M \quad \text{Eq. 2}$$

Where:

TQ_m : Total Quantity of material m that must be stored (Table 7)

Maximum storage capacity

To simplify the model, all available warehouses are ECM mentioned in chapter 3.1. The dimensions of these warehouses vary depending on the needs. In the given thesis, the width is 24 m and the length is 8 m. Therefore, the available surface area is 192 m². In many cases, due to the sensitivity of the materials, packages must not be stacked on top of each other. Therefore, the packages will be placed exclusively on the available surfaces of the warehouses (Whole Building Design Guide, 2015).

To find the area occupied by the packages of the materials in Excel the followings steps took place. First, the number of materials (Table 9) was divided by the number of material per package (Table 4) to calculate the total number of packages, which was then rounded up to the closest integer to avoid non-integer number of packages. Here, we assume that each material is packed in packages of specific size. Then, the number of packages was multiplied by the area each package occupies (Table 6). Last, the capacity restriction is applied ensuring that the packages' area is lower than the total capacity of the warehouse (see Eq. 3).

$$\sum_{m=1}^M (P_{w,m} \cdot A_m) \leq TC_w, \text{ for } w = 1, 2, \dots, W \quad \text{Eq. 3}$$

Where:

$P_{w,m}$: Packages of material m in warehouse w

A_m : Area of an individual package containing material m (Table 6)

TC_w : Total capacity (expressed in area units) of warehouse w

Maximum net explosive weights

According to the American Unified Facilities Criteria (UFC) manual, the maximum quantity of explosives that can be stored within ECMs is 500,000 lbs. To simplify the model, all

warehouses satisfy the distance criteria (discussed in chapter 3.2), so they can store the maximum quantity of explosives, as indicated by UFC (Whole Building Design Guide, 2015).

To calculate the total mass of explosives in each warehouse, the quantities of materials (Table 9) were multiplied by their corresponding Net Explosive Weight (NEW) (Table 5). The summary of this product for each warehouse should be lower than UFCs limit (500,000 lbs). This restriction is expressed in Eq. 4.

$$\sum_{m=1}^M (Q_{w,m} \cdot NEW_m) \leq TEW_w, \text{ for } w = 1, 2, \dots, W \quad \text{Eq. 4}$$

Where:

$Q_{w,m}$: Quantity of material m in warehouse w

NEW_m : Net Explosive Weight of material m (Table 5)

TEW_w : Total Explosive Weight limit of warehouse w

Compatibility checks

As mentioned in Chapter 2.2.2, not all materials can be stored together for safety reasons. A compatibility check should be made according to the Table 1. As can be understood from Table 1 and Table 8, all materials can be stored together except materials 2 and 3 which can be stored only with material 5.

To ensure compatibility restrictions across the warehouses, all possible combinations of the restrictions were considered. These restrictions primarily apply to materials 2 and 3. Specifically, storing one of these materials in a warehouse prohibits the storage of other materials there, except for material 5.

Furthermore, any possible storage position for material 2 in a warehouse corresponds to exactly four possible storage positions for material 3, and vice versa. For example, if material 2 is stored in warehouse 1, material 3 can be stored in warehouses 2, 3, 4, or 5. Since material 2 can be stored in all warehouses, 20 possible combinations arise, which are summarized in Table 10.

Table 10. Possible compatibility combinations

Combination	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Material 2	W1				W2				W3				W4				W5			
Material 3	W2	W3	W4	W5	W1	W3	W4	W5	W1	W2	W4	W5	W1	W2	W3	W5	W1	W2	W3	W4

Next, for all these possible combinations a different Solver scenario was created described by Eq. 5 and Eq. 6. Taking care to ensure that material 3 is not placed in the same warehouses as material 2.

$$Q_{w,2} \neq 0 \rightarrow Q_{w,m} = 0, \forall m \neq 2, 5 \quad \text{Eq. 6}$$

$$Q_{w,3} \neq 0 \rightarrow Q_{w,m} = 0, \forall m \neq 3, 5 \quad \text{Eq. 7}$$

Based on the above, auxiliary tables were created containing zero values and values of 10^9 , which is significantly larger than the available quantities to be stored. This was done to allow the Solver to freely allocate materials to specific warehouses. A total number of 20 auxiliary tables were created, corresponding to each possible combination from Table 10. Additionally, it was established that the table of decision variables must consist of natural numbers. Thus, the constraint applied is given in Eq. 8.

$$Q_{w,m} \leq AT_{w,m}, \forall w, m \quad \text{Eq. 9}$$

Where:

$Q_{w,m}$: Quantity of material m in warehouse w

$AT_{w,m}$: Value of auxiliary table of material m in warehouse w

For example, in the case where material 2 is stored in warehouse 1 and material 3 is stored in warehouse 2, the auxiliary table is as follows in Table 11. Auxiliary Table

Table 11. Auxiliary Table

	Auxiliary Table						
	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5	Mat 6	Mat 7
W1	0	2000	0	0	1.00E+09	0	0
W2	0	0	6000	0	1.00E+09	0	0
W3	1E+09	0	0	1E+09	1.00E+09	1E+09	1E+09
W4	1E+09	0	0	1E+09	1.00E+09	1E+09	1E+09
W5	1E+09	0	0	1E+09	1.00E+09	1E+09	1E+09

Restriction for combined material-warehouse attractiveness

According to chapters 2.2.3 and 3.3, not all materials can be stored in every warehouse. Materials 1, 6, and 7, with medium attractiveness levels, cannot be stored in Warehouse 1, which has the poorest safety levels. Furthermore, Materials 4 and 5, the most attractive materials, cannot be stored in Warehouses 1, 2, and 3, which are characterized by low levels of security. To enforce these restrictions the Storage Check (Eq. 5) variable is set to 0 for aforementioned combinations of materials and warehouses. These restrictions are expressed in Eq. 10.

$$SC_{1,1} = SC_{1,6} = SC_{1,7} = SC_{1,4} = SC_{1,5} = SC_{2,4} = SC_{2,5} = SC_{3,4} = SC_{3,5} = 0 \quad \text{Eq. 10}$$

5 Results

After running the 20 scenarios in Solver, the results for the objective functions are presented in Table 12. We observe that four combinations minimize the objective function with a value of 3,016,500. These combinations are marked with a light blue color in Table 12. The fact that four different combinations occur as optimal solutions is due to multiple warehouses, materials, and their combinations corresponding to the same risk level, which in turn leads to the same risk value. This increases the possibility of multiple combinations leading to the same objective function value. For example, storing materials 2 and 3 either in warehouses 1 and 2 or 1 and 3, respectively, gives an objective function value of 3,024,500. The same also applies to the optimal solution, where materials 2 and 3 can be optimally stored either in warehouses 2 and 4, 2 and 5, 3 and 4 or 3 and 5, respectively, leading to an objective function value of 3,016,500.

Table 12. Objective functions

Material 2	Material 3	Objective Function
Warehouse 1	Warehouse 2	3024500
Warehouse 1	Warehouse 3	3024500
Warehouse 1	Warehouse 4	3018500
Warehouse 1	Warehouse 5	3018500
Warehouse 2	Warehouse 1	3028500
Warehouse 2	Warehouse 3	3022500
Warehouse 2	Warehouse 4	3016500
Warehouse 2	Warehouse 5	3016500
Warehouse 3	Warehouse 1	3028500
Warehouse 3	Warehouse 2	3022500
Warehouse 3	Warehouse 4	3016500
Warehouse 3	Warehouse 5	3016500
Warehouse 4	Warehouse 1	3026500
Warehouse 4	Warehouse 2	3020500
Warehouse 4	Warehouse 3	3020500
Warehouse 4	Warehouse 5	3021000
Warehouse 5	Warehouse 1	3026500
Warehouse 5	Warehouse 2	3020500
Warehouse 5	Warehouse 3	3020500
Warehouse 5	Warehouse 4	3021000

Solution 1: Materials 2 and 3 stored in warehouses 2 and 4

Table 13 the distribution of materials in the warehouses for the cases where material 2 is stored in warehouse 2 and material 3 in warehouse 4. Table 14 presents the occupation levels and the total Net Explosive Weight (NEW) as well as their corresponding for each warehouse. Besides materials 2 and 3, the Solver chooses to store all of the remaining materials in warehouse 5, to reduce the risk of theft since the rest of the available warehouses have lower security measures. In other words, the selection of warehouse 5 ensures that the objective

function will take the lowest possible value, minimizing the total risk of theft. From Table 14 we observe that the area of warehouse 5 is filled with 89% (171 m² occupied out of 192 m² available). For the rest of the warehouses, the occupied space is much lower than the area limit. Additionally, the NEW stored in all warehouses is also much lower than the corresponding limit. Last, warehouses 1 and 3 were selected from the solver to be empty.

Table 13. Quantities when material 2 is stored in warehouse 2 and material 3 in warehouse 4,

	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5	Mat 6	Mat 7
W1	0	0	0	0	0	0	0
W2	0	2000	0	0	0	0	0
W3	0	0	0	0	0	0	0
W4	0	0	6000	0	0	0	0
W5	100	0	0	1500	1000000	400	500

Table 14. Occupied Area and NEW per warehouse when material 2 is stored in warehouse 2 and material 3 in warehouse 4,

	Occupied Area	Total capacity	NEW	Explosive weight limit
	[m ²]			[lbs]
Warehouse 1	0.00	<192	0	<500,000
Warehouse 2	0.11		10	
Warehouse 3	0.00		0	
Warehouse 4	17.42		3452.46	
Warehouse 5	171.11		7731.54	

Table 15 presents the hazard of possible accidents resulting from misuse of the stored materials, as discussed in Chapter 2.2.1. The final hazard for each warehouse is equal to the hazard level of the most hazardous material stored within it. In this system's evaluation scale, a lower indicator value signifies a higher hazard (e.g., 1.1 is more hazardous than 1.2). For example, in warehouse 5, where four materials are co-stored, the hazard level is that of the most hazardous materials, which are materials 4 and 7 with a hazard level of 1.1. Thus, warehouses 4 and 5 are the most hazardous, having a hazard level of 1.1, which corresponds to possible massive explosions in case of material misuse. Warehouse 2, on the other hand, presents a small risk of accident, as the indicator value of 1.4 suggests that possible material reactions will be limited to within their packaging.

Table 15. Hazard Divisions of each warehouse when material 2 is stored in warehouse 2 and material 3 in warehouse 4,

Hazard Divisions	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	
	1.1	1.4	1.1	1.1	1.4	1.3	1.1	
Warehouse 1								
Warehouse 2		1.4						1.4
Warehouse 3								
Warehouse 4			1.1					1.1

Warehouse 5			1.1	1.4	1.3	1.1	1.1
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Solution 2: Materials 2 and 3 stored in warehouses 2 and 5

Table 16 shows the material storage arrangement when material 2 is placed in warehouse 2 and material 3 in warehouse 5. In this scenario, the Solver placed all remaining materials, except material 5, in warehouse 4. Material 5 is assigned to warehouse 5, again minimizing the objective function. It should be noted that material 5 could also be placed in warehouse 4, resulting in the same objective function value. The Solver did not identify this as an alternative optimal solution, as it typically provides only one solution when multiple optimal solutions exist. Therefore, the Solver’s solution (material 5 in warehouse 5) and the alternative (material 5 in warehouse 4) are equivalent. Table 17 shows the total area occupied by materials within each warehouse and the quantity of stored explosive material. Compared to the previous optimal solution, a greater material dispersion is observed. Warehouse 5 is 75% occupied. Table 18 shows that, again, two warehouses have a hazard level of 1.1 (warehouses 4 and 5), while warehouse 2 has a lower hazard level of 1.4.

Table 16. Table of quantities when material 2 is stored in warehouse 2 and material 3 in warehouse 5,

	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5	Mat 6	Mat 7
W1	0	0	0	0	0	0	0
W2	0	2000	0	0	0	0	0
W3	0	0	0	0	0	0	0
W4	100	0	0	1500	0	400	500
W5	0	0	6000	0	1000000	0	0

Table 17. Occupied Area and NEW per warehouse when material 2 is stored in warehouse 2 and material 3 in warehouse 5,

	Occupied Area	Total capacity	NEW	Explosive weight limit
	[m2]			[lbs]
Warehouse 1	0.00	<192	0	<500,000
Warehouse 2	0.11		10	
Warehouse 3	0.00		0	
Warehouse 4	44.11		4731.54	
Warehouse 5	144.42		6452.46	

Table 18. Hazard Divisions of each warehouse when material 2 is stored in warehouse 2 and material 3 in warehouse 5,

Hazard Divisions	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	
	1.1	1.4	1.1	1.1	1.4	1.3	1.1	
Warehouse 1								
Warehouse 2		1.4						1.4
Warehouse 3								

Warehouse 4	1.1			1.1		1.3	1.1	1.1
Warehouse 5			1.1		1.4			1.1

Solution 3: Materials 2 and 3 stored in warehouses 3 and 4

Table 19 presents the storage configuration when materials 2 and 3 are assigned to warehouses 3 and 4, respectively. Similar to solution 1, the Solver allocates all remaining materials to warehouse 5. Table 20, which details the total area occupied by materials within each warehouse and the amount of explosive material stored, presents the same distribution level as that of solution 1, with the difference that material 2 is forced to be stored in warehouse 3 instead of warehouse 2. Again, warehouse 5 reaches 89% capacity. Looking at Table 21 we observe the same recurring pattern as in the previous solutions: two warehouses (4 and 5) exhibit a high hazard level of 1.1, while warehouse 3 maintains a low hazard level of 1.4. This suggests that while the specific materials assigned to each high-hazard warehouse may vary, the overall risk profile, with two high-hazard locations and one low-hazard location, remains consistent across all solutions.

Table 19. Table of quantities when material 2 is stored in warehouse 3 and material 3 in warehouse 4,

	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5	Mat 6	Mat 7
W1	0	0	0	0	0	0	0
W2	0	0	0	0	0	0	0
W3	0	2000	0	0	0	0	0
W4	0	0	6000	0	0	0	0
W5	100	0	0	1500	1000000	400	500

Table 20. Occupied Area and NEW per warehouse when material 2 is stored in warehouse 3 and material 3 in warehouse 4,

	Occupied Area	Total capacity	NEW	Explosive weight limit
	[m2]			[lbs]
Warehouse 1	0.00	<192	0	<500,000
Warehouse 2	0.00		0	
Warehouse 3	0.11		10	
Warehouse 4	17.42		3452.46	
Warehouse 5	171.11		7731.54	

Table 21. Hazard Divisions of each warehouse when material 2 is stored in warehouse 3 and material 3 in warehouse 4,

Hazard Divisions	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	
	1.1	1.4	1.1	1.1	1.4	1.3	1.1	
Warehouse 1								
Warehouse 2								
Warehouse 3		1.4						1.4

Warehouse 4			1.1					1.1
Warehouse 5	1.1			1.1	1.4	1.3	1.1	1.1

Solution 4: Materials 2 and 3 stored in warehouses 3 and 5

This solution is nearly identical to solution 2, differing only in the placement of material 2. Here, it is stored in warehouse 3, whereas it was in warehouse 2 in solution 2 (Table 22). The capacity of warehouse 5 remains at 75%, and the NEW for each warehouse is significantly lower than the restrictions (Table 23). Finally, Table 24 shows that the consistent pattern of two warehouses with a hazard level of 1.1 and one warehouse with a hazard level of 1.4 is also observed in this solution.

Table 22. Table of quantities when material 2 is stored in warehouse 3 and material 3 in warehouse 5,

	Mat 1	Mat 2	Mat 3	Mat 4	Mat 5	Mat 6	Mat 7
W1	0	0	0	0	0	0	0
W2	0	0	0	0	0	0	0
W3	0	2000	0	0	0	0	0
W4	100	0	0	1500	0	400	500
W5	0	0	6000	0	1000000	0	0

Table 23. Occupied Area and NEW per warehouse when material 2 is stored in warehouse 3 and material 3 in warehouse 5,

	Occupied Area	Total capacity	NEW	Explosive weight limit
	[m2]			[lbs]
Warehouse 1	0.00	<192	0	<500,000
Warehouse 2	0.00		0	
Warehouse 3	0.11		10	
Warehouse 4	44.11		4731.54	
Warehouse 5	144.42		6452.46	

Table 24. Hazard Divisions of each warehouse when material 2 is stored in warehouse 3 and material 3 in warehouse 5

Hazard Divisions	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	
	1.1	1.4	1.1	1.1	1.4	1.3	1.1	
Warehouse 1								
Warehouse 2								
Warehouse 3		1.4						1.4
Warehouse 4	1.1			1.1		1.3	1.1	1.1
Warehouse 5			1.1		1.4			1.1

6 Conclusion and future work

This thesis optimizes the storage of explosives and ammunition across multiple warehouses, considering the classification of explosives based on potential consequences of misuse, material compatibility, and theft risk based on material attractiveness. Different warehouse types with varying characteristics and restrictions, as defined by NATO and US standards, are also taken into account. A theft risk objective function, combining material theft risk and warehouse security levels, is used. Optimal storage configurations are determined by minimizing this objective function using Microsoft Excel's Solver tool.

Due to the compatibility group restrictions for the materials, 20 storing scenarios occurred from which the optimal solution emerged. Analysis of these 20 scenarios revealed four distinct optimal storage combinations that minimize the defined objective function. These optimal solutions demonstrate that multiple warehouse-material combinations can result in equivalent risk levels, leading to the same overall objective function value of 3,016,500 (risk of theft). This multiplicity arises because different pairings of materials and warehouses can contribute similarly to the overall risk. For instance, the placement of certain material pairs in different warehouse combinations resulted in the same overall risk score (objective function value). This suggests a degree of flexibility in achieving optimal storage configurations.

The optimal solutions consistently favored the concentration of most materials, excluding certain key pairings, in one of the warehouses with the highest security measures (warehouse 5). This strategy effectively minimized the overall theft risk by leveraging the superior security of that specific warehouse. While the specific placement of a critical material pair varied across the four optimal solutions, the general pattern of concentrating the remaining materials in the most secure warehouse remained consistent. This indicates that maximizing security for the bulk of the stored materials is a key factor in achieving optimal storage configurations.

Quantitatively, the optimal solutions achieved the lowest possible objective function value, demonstrating the effectiveness of the optimization process. Qualitatively, the solutions consistently exhibited a pattern of concentrating materials in the most secure warehouses. The results demonstrate the model's ability (Microsoft Excel Solver) to identify multiple, practically viable solutions that balance security and material compatibility considerations.

Future work could explore incorporating additional factors into the objective function, such as transportation costs between warehouses and material handling expenses. Furthermore, investigating alternative optimization algorithms beyond the Excel Solver could potentially identify even more efficient solutions or handle more complex scenarios with a larger number of materials and warehouses. Expanding the model to include dynamic factors, like fluctuating material availability or changes in security levels, would further enhance its practical applicability. Finally, a sensitivity analysis could be performed to assess the impact of variations in input parameters, such as material attractiveness and warehouse security levels, on the optimal storage configurations.

References

- Arsenal BG. (n.d.). *30x165mm rounds for aircraft automatic guns*. Retrieved from <https://www.arsenal-bg.com/c/30x165-mm-rounds-for-aircraft-automatic-guns-gsh-30-gsh-30k-gsh-6-30-and-gsh-301-138/heihe-thei-t-222>
- Arsenal Defense. (2025). *HE 30x165 air specifications*. Retrieved from https://arsenal-defense.com/wp-content/uploads/spec-sheets/HE_30x165_AIR.pdf
- Briones, L., Morales, V., Iglesias, J., Morales, G., & Escola, J. M. (2020). Application of the Microsoft excel solver tool in the optimization of distillation sequences problems. *Computer Applications in Engineering Education*, 28(2), 304-313.
- Air Force Manual 91-2019. (2019). *AFMAN 91*.
- DDPDOO. (n.d.). *30mm HE cartridges*. Retrieved from <https://ddpdoo.gov.in/product/products/product-details/cartg-30-mm-he>
- Erkut, E., Tjandra, S. A., & Verter, V. (2007). Hazardous materials transportation. *Handbooks in Operations Research and Management Science*, 14, 539–621.
- Federal Motor Carrier Safety Administration. (2013). *Nine classes of hazardous materials*. Retrieved from https://www.fmcsa.dot.gov/sites/fmcsa.dot.gov/files/docs/Nine_Classes_of_Hazardous_Materials-4-2013_508CLN.pdf
- Lentzis. (2025). *Sellier & Bellot 9mm Luger 115-gr FMJ bullets*. Retrieved from <https://www.lentzis.com/shop/fysiggia/sfares/sfares-sellier-amp-bellot-9-mm-luger-115-grs-fmj/>
- Militaria Plaza. (2025). *TNT 1-pound high explosive charge*. Retrieved from <https://militariaplaza.nl/us/empty-us-tnt-1-pound-high-explosive-charge-detail>
- NATO Standardization Office. (2023). *AASTP-1: Manual of NATO safety principles for the storage of ammunition and explosives*.
- NATO Standardization Office. (2010). *AASTP-3: Manual of NATO principles for transporting ammunition by road and rail*.
- NATO Standardization Office. (2016). *AASTP-5: Manual of NATO principles for ammunition process safety*.
- Outdoor Limited. (n.d.). *9mm ammunition: History, specifications, and types*. Retrieved from <https://outdoorlimited.com/blog/9mm-ammunition-history-specifications-and-types-of-9mm-ammo/>

Simplilearn. (2024). *Solver in Excel: A tutorial*. Retrieved from <https://www.simplilearn.com/tutorials/excel-tutorial/solver-in-excel>

Tara Aerospace. (2025). *MJU-7A/B*. Retrieved from <https://www.tara-aerospace.com/MJU-7A-B>

Tara Aerospace. (2025). *UD-M76P1*. Retrieved from <https://www.tara-aerospace.com/UD-M76P1>

Tara Aerospace. (2025). *URM-1*. Retrieved from <https://www.tara-aerospace.com/URM-1>

U.S. Army. (2019). *AR 190-11: Physical security of arms, ammunition, and explosives*. Retrieved from <https://www.mass.gov/doc/ar-190-11-physical-security-of-arms-ammunition-and-explosives/download>

U.S. Department of Defense. (2020). *DoDM 5100.76-M: Physical security of conventional arms, ammunition, and explosives*. Retrieved from <https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodm/510076m.pdf>

U.S. Environmental Protection Agency. (2014). *Contaminant fact sheet: TNT*. Retrieved from https://19january2017snapshot.epa.gov/sites/production/files/2014-03/documents/ffrofactsheet_contaminant_tnt_january2014_final.pdf

WBParts. (n.d.). *Product RFQ for 1377-00-119-2055*. Retrieved from <https://www.wbparts.com/rfq/1377-00-119-2055.html>

Whole Building Design Guide. (2015). *UFC 4-420-01: 2015 C1 archive*. Retrieved from https://www.wbdg.org/FFC/DOD/UFC/ARCHIVES/ufc_4_420_01_2015_c1.pdf

WorthPoint. (2024). *Martin-Baker Mk92 rocket motor cast*. Retrieved from <https://www.worthpoint.com/worthopedia/martin-baker-mk92-rocket-motor-cast-1879397577>

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