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Original Article

Optimal Allocation of Ammunition Stores Based on Graph Coloring Theory

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Abstract:
In the contemporary context of informationized warfare, the efficient and reliable storage and supply of ammunition is imperative to enhance the combat effectiveness and battlefield survivability of troops. This is particularly salient when field ammunition depots are confronted with the formidable challenge of enemy threats. Despite the fact that prevailing ammunition distribution methodologies take into account distance, scale, and storage characteristics, they tend to overlook the resilience of ammunition supply in the aftermath of an attack by the enemy. This oversight leads to models that prioritize cost and time, rather than aligning with the actual operational requirements. The objective of this study is to address this critical issue by innovatively applying graph coloring theory to model the ammunition-storage allocation problem as a Box-Building Problem with Conflict Constraints (BBPC) in order to optimize the ammunition allocation strategy for field ammunition depots. The model's objective is to minimize the number of required depots while ensuring that conflicting munitions do not coexist in the depots. This is achieved by mapping munitions types as vertices of the graph and non-coexistence relationships between munitions as edges. The mathematical model meticulously delineates the decision variables and constraints, with the objective of attaining an optimal allocation of munitions that aligns with the conflict constraints. While the algorithm demonstrates proficiency in terms of convergence and the allocation of ammunition types in a progressive and efficient manner, preliminary findings indicate a substantial load imbalance. This study offers significant theoretical and practical value in enhancing the storage efficiency and overall ammunition safeguard capability of field ammunition depots. In the future, the focus will be on optimizing the algorithm to achieve a more balanced distribution of depot loads and further enhance the destructive resistance of the ammunition supply and safeguard system.

Keywords: Graph Coloring Theory; Ammunition-Store Allocation; Field Ammunition Depot; Conflict Constraints; Supply Assurance Resilience; BBPC Model

1. Introduction

As the core material foundation of military operations, the efficient and reliable storage and supply of ammunition directly determines the combat effectiveness and battlefield survivability of troops. In the context of information-based warfare, ammunition depots at all levels, especially field ammunition depots configured at the front line, are facing increasingly serious potential threats. Due to their geographic location and structural characteristics, the survivability of different depots varies when they are hit by the enemy, and once damaged, the munitions in the depots will suffer huge losses. Therefore, how to optimize the distribution strategy of ammunition storage under the premise of comprehensively considering the survivability of ammunition, so as to significantly improve the overall supply guarantee capability of ammunition depots, has become a key issue that needs to be studied in depth in the field of military logistics and asset management. Scientific and reasonable ammunition storage is of great theoretical and practical significance for improving the survivability of ammunition and effectively enhancing the ammunition guarantee capability.

Currently, the practice of ammunition depot allocation is mainly based on the following principles: first, based on the demand and distance between field ammunition depots and combat units, a "field ammunition depot-combat unit" supply network is constructed, with high-demand munitions being placed in front of them, in order to save transportation costs and ensure the timeliness of supply. Secondly, considering the scale and location of field ammunition depots, priority should be given to those depots with large scale, many transportation routes and sufficient capacity, so as to optimize transportation and speed up receiving and dispatching tasks. Lastly, taking into account the storage life and characteristics of ammunition, priority is given to the allocation of old ammunition and strict adherence is given to the principle of separate storage of non-co-existing ammunition in separate warehouses. Existing practice, however, tended to focus on operational efficiency and cost control, with insufficient consideration given to the resilience of ammunition depots in terms of security of supply in the event of an enemy strike, which posed a significant risk in the complex and volatile environment of the modern battlefield.

In the field of decision-making on ammunition supply and security, scholars at home and abroad have conducted many studies. Domestically, Yang Qingwen et al. pointed out that our army has problems such as low level of informationization and main reliance on mechanized supply in decision-making of ammunition supply and reserve. Zhao Mei discussed the ammunition supply chain from the perspective of system dynamics, Song Chao on field environment storage, Li Kai et al. on multi-objective scheduling model optimization, and Liu Haobang et al. on the construction of supply and security system and effectiveness evaluation. Qi Ling proposed the ammunition supply evaluation model based on satisfaction rate, which provides new ideas for optimizing the inventory structure. Meanwhile, the research on the research and development of insensitive ammunition, the decision-making of ammunition consumption and the influencing factors of precise guarantee capability also provides reference for the construction of ammunition guarantee capability. However, our army still faces challenges such as cumbersome requisition and distribution procedures, poor information sharing, outdated operational tools and irrational layout of ammunition warehouses in ammunition supply and security decision-making. To this end, researchers have proposed a series of new ammunition security methodologies and decision-making methods, such as Agent-based intelligent decision-making system, wartime-oriented ammunition supply dispatch model, ammunition supply security federal design, low-consumption ammunition supply simulation model, and aviation ammunition supply chain inventory control strategy, which provide new ideas for decision-making. The U.S. Army implements a four-level supply system of headquarters-theater-army-division (brigade) in ammunition security, and has established multi-level ammunition supply organizations in the theater. Its ammunition supply decision-making mainly considers six parts, such as maneuver distribution, ammunition reserve, means of replenishment, packaging, loading and unloading, and distribution, and pays attention to the optimization of packaging and transportation and distribution means. Chai Jiaqi and Li Kang et al. have conducted in-depth analyses of the U.S. Army's ammunition security decision-making from the aspects of security mode, security mechanism and ammunition demand projection, respectively. However, the existing research generally focuses on the allocation of ammunition quantity based on past consumption data, and lacks in-depth consideration of the supply capacity of ammunition varieties after being hit by the enemy. In modeling, cost and time should not be the only objectives, and the resilience of ammunition supply assurance after damage to the ammunition depot should be considered from the perspective of actual combat.

Graph coloring theory, as an important branch of graph theory, provides a powerful theoretical framework for solving complex combinatorial optimization problems. By abstracting the problem as a graph coloring problem, the theory aims to find an optimal coloring scheme that makes adjacent vertices or edges have different colors, which shows great potential in the fields of resource allocation, scheduling optimization and network design.

It is on the basis of the above background and shortcomings that this paper takes the field ammunition depot as the research object, and aims to optimize the allocation strategy of ammunition-storage. It is of great theoretical significance and practical value to improve the storage efficiency of field ammunition depots and comprehensively enhance the efficiency of ammunition safeguarding, and its core objective is to realize scientific and reasonable ammunition storage, so as to significantly enhance the survivability and overall safeguarding capability of ammunition.

2 Ammunition with non-co-existing rounds - stockpile allocation

2.1 Graph Coloring Model

- The graph structure is usually represented by $G=(V, E)$, which contains a vertex set V and an edge set E. The vertex set V describes the set of objects associated with the research problem, and the edge set E describes the set of specific relationships between the objects.
- For a given graph structure $G=(V, E)$, the vertex coloring process is to assign the colors in a color set to each vertex in V on a one-to-one basis and ensure that no two adjacent vertices (with edges adjoining each other in existence) in G have the same color, the optimization goal of the process is to minimize the number of colors used.
- Given $G=(V, E)$, the process of coloring the set of vertices using a set of at least k colors $N=\{1,2,\ldots,k\}$ can be described as a mapping relation $f: V \rightarrow N$,where, for any two distinct vertices $v_i, v_j \in V$,if there exists $(v_i, v_j) \in E$, then there is $f(v_i) \neq f(v_j)$. The coloring of the ten vertices is shown in Figure 1

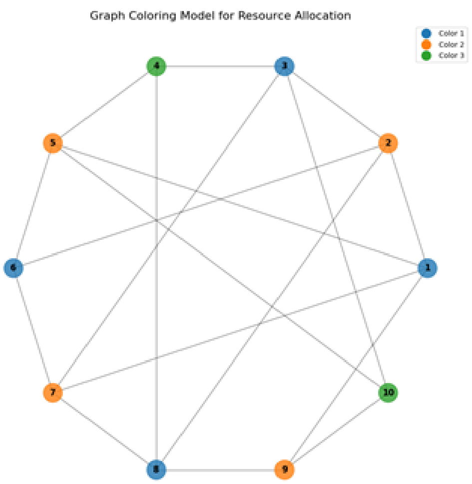

Figure 1 Graph coloring model for resource allocation

For the above definition, the mathematical planning model of the vertex coloring problem can be further generalized by assuming that the set of optional colors for the vertices is $C_i=\{1,2,\ldots,n\}$, and the decision variables in the model are:

$$x_{ij}=\begin{cases}1, & \text{vertex i has color j}\\ 0, & \text{else}\end{cases} \qquad (1)$$

Then the mathematical model for the vertex coloring problem is as follows.

$$\min f(x)=\sum_{k=1}^{n}\delta(\sum_{l=1}^{n}x_{ik}) \qquad (2)$$

$$s.t.\begin{cases}\sum_{k\in C} x_{ik} = 1, 1 \le i \le n \\ G_k(x) = \sum_{(v_i,v_j)\in E} x_{ik} \cdot x_{ij} = 0, 1 \le i \le n \quad (3) \\ x_{ij} \in \{0,1\}, 1 \le i \le n, j\end{cases}$$

In the above model, δ is expressed as a 0-1 function, that is

$$\delta(z)=\begin{cases}1, & z>0 \\ 0, & \text{else}\end{cases} \qquad (4)$$

The function constrains the colors of adjacent vertices to ensure that the same color is not selected. The overall optimization goal of the model is to minimize the number of colors used.

2.2 The requirement of non-coexistence of ammunition types

The problem of assigning ammunition types to storage depots can be efficiently modeled as a graph-coloring problem, taking into account the conflict relationships between different ammunition. By building a graph-theoretic model, the ammunition-storage allocation problem is transformed into a graph-coloring problem with conflict constraints, thus obtaining a generic solution framework for the problem. The intrinsic connection between graph-theoretic modeling and the ammunition-storage allocation problem is manifested in three main ways:

(i) In the ammunition-depot allocation problem, ammunition types and their conflict relations can be mapped to vertex attributes and edge attributes of the graph, respectively. The ammunitions-storage allocation problem with conflict relations is transformed into a graph coloring problem with conflict relations for representation.

Bullet species with the point set V, the non-coexistence relationship between the bullet species with the edge set E, will have a non-coexistence relationship between the two bullet species with the edge $e(v_i, v_j)$ connection, the two points connected to each other can not be dyed the same color, that is, the two have a non-coexistence relationship between the two types of bullets can not be coexisting in the same storage.

(ii) Using graph-theoretic data structures such as adjacency matrices or adjacency tables, which can efficiently store conflict relationships between munitions, can efficiently store conflict relationships between munitions, this representation can both ensure the integrity of data storage and enhance the efficiency of algorithm execution.

(iii) Graph theory has developed a complete theoretical system containing a variety of classical models and efficient algorithms that have been rigorously mathematically proven. By formalizing the ammunition-storage allocation problem as a graph-coloring model, the well-established optimization methods in graph theory can be directly applied.

In practical applications, this study further abstracts the ammunition-store allocation problem into the Boxing with Conflict Constraints (BPPC) problem based on the classical vertex coloring model. The subsequent discussion will focus on the construction of the BPPC problem model and the design of the solution algorithm.

3. Modeling of Ammunition-Store Allocation Based on BPPC

The BPPC problem is modeled as given a collection of bullet lists, where the bullet attributes are mainly conflict relationships between bullet types, and the ammunition depot attributes are mainly the maximum ammunition type storage limitations of the depot, the problem optimization objective is to complete the allocation operation of the ammunition-depot under the premise of satisfying the conflict relationship constraints between the bullet types and to make the required ammunition depot the least.

3.1 Model Definition

The set of vertices CV corresponds to the combination of munitions to be assigned, and each of these vertices has an attribute value indicating the type of munition; the set of edges CE corresponds to the conflict relationship between munitions, i.e., two munitions corresponding to two vertices adjacent to an edge are not allowed to be loaded into the same container for storage and transportation. Define the following variables：

I represents collection of ammunition types， H represents ammunition depot collection， C represents the maximum number of ammunition types that can be stored in each ammunition depot in H ,The set of ammunition types that have conflicting relationships with ammunition type L_i .

The graph structure $CG=(CV,CE)$ describes the conflict relationship between bullet species, record $CG=(CV,CE)$, to represent the conflict relationship between bullet species and bullet species.The vertex set CV denotes the set of all bullet seeds, and any side $(i,j)\in CE$ in the graph indicates that there is a conflict relationship between bullet seed i and bullet seed j. In order to facilitate the elimination of conflict relations and subsequent packing operations, the edge CE in the conflict graph needs to be extended as follows: for any bullet see $i\in I$, an edge is added between each bullet seed in the list of conflict relations L_i corresponding to it.

The conflict relationship between the ammunitions to be assigned is expressed in the form of a conflict diagram structure, and it is also necessary to consider the method of storing the diagram structure in the computer, in order to facilitate search and calculation. The method of adjacency matrix is chosen to represent the conflict diagram in Figure 2.

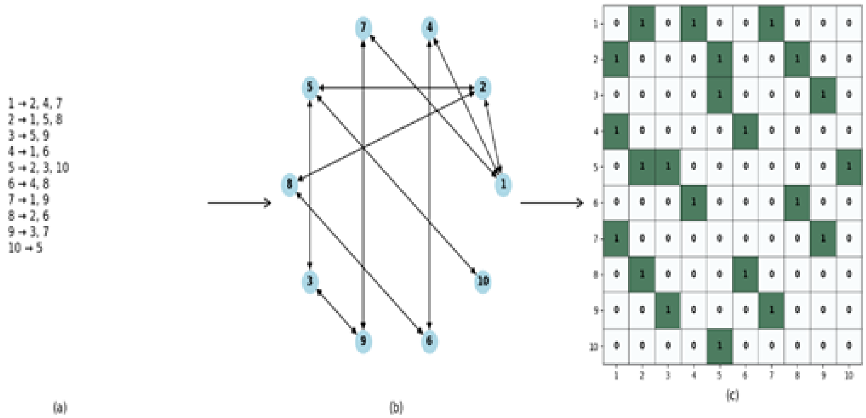

Figure 2 Conflict Relationship Diagram

3.2 Model Establishment

The conflict relationship diagram visually maps the allocation problems with conflicting relationships onto an undirected graph structure, thereby enabling the subsequent definition of the corresponding integer programming model.

The decision variables are defined as

$$y_h=\begin{cases}1 & \text{the hth ammunition depot}\\ 0 & \text{else}\end{cases} \quad i\in I;h\in H \qquad (5)$$

$$x_{ih}=\begin{cases}1 & i \text{ in storage } h\\ 0 & else\end{cases} ;\quad i\in I;h\in H \qquad (6)$$

Based on the above model variables, the conflict relationship diagram and decision variables, the mathematical model of the ammunition-warehouse allocation problem with conflict relationships can be described as follows:

$$\min \sum_{h=1}^{n} y_h \qquad (7)$$

$$\sum_{h=1}^{n} x_{ih} \geq 1, i \in I \qquad (8)$$

$$x_{ih} + x_{jh} \leq y_h, (i, j) \in CE, h \in H \qquad (9)$$

$$y_h \in \{0,1\}, h \in H \qquad (10)$$

$$x_{ih} \in \{0,1\}, i \in I, h \in H \qquad (11)$$

where Eq. (7) is the objective function, i.e., to allocate all munitions to the depot and to minimize the number of magazines required under the condition that the restrictions on the conflict relationship between munitions types are satisfied; Eq. (8) indicates that any type of munitions must be put into the depot; Eq. (9) utilizes the conflict relationship diagram and adopts the 0-1 variable to define the conflict relationship between munitions types. Eqs. (10) and (11) represent the corresponding decision variables and ranges of values for the selection of ammunition types and ammunition allocation.

3.3 Model solution

After eliminating the conflict relationship, it is necessary to complete the allocation of ammunition-storage, and design a responsive heuristic heuristic ammunition-storage allocation algorithm for all sets of ammunition seeds that do not have a conflict relationship, so as to realize the allocation of ammunition-storage with the least number of ammunition stores.

Input the ammunition type conflict matrix in Eq. (12), and the output result is 3. Then, using 3 ammunition storage rooms can complete the allocation of ammunition and storage rooms. The result is shown in Fig 4.

Fig.4 visually presents the dynamic process of ammunition-cum-storage facility allocation based on the graph coloring algorithm, which is divided into four key stages. Each node in the figure represents a specific type of ammunition, and the edges connecting the nodes clearly indicate the conflicting relationships between these ammunition types, meaning they cannot be stored together in the same storage facility.

$$x = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \qquad (12)$$

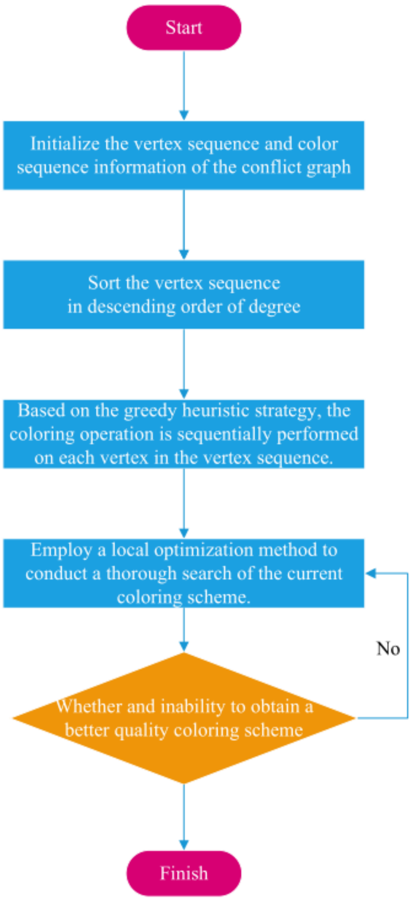

Figure 3 Heuristic Ammunition - Warehouse Allocation Algorithm

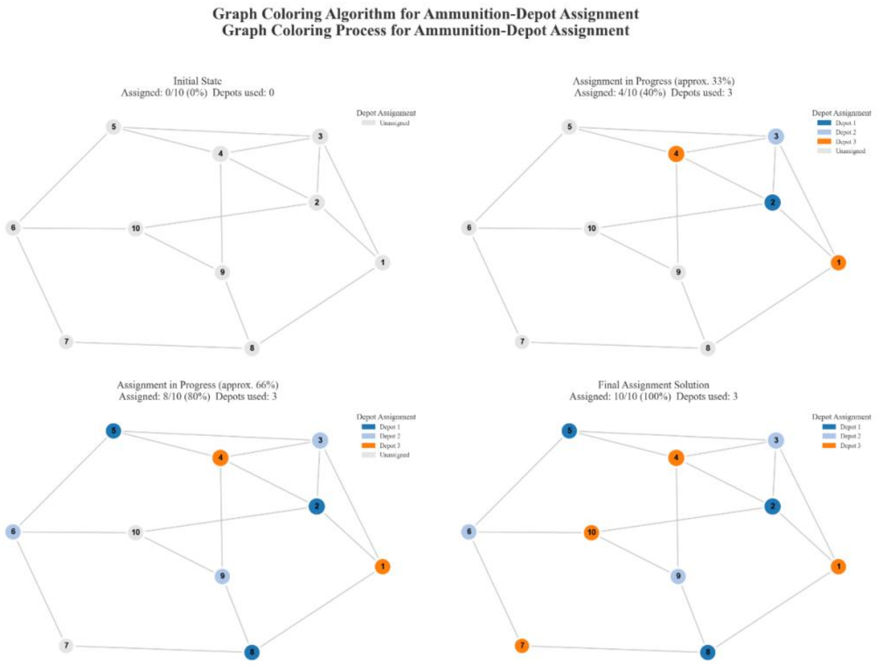

Figure 4 Heuristic Ammunition - Warehouse Allocation Algorithm

Different colors are used to distinguish the ammunition allocated to different storage facilities, and through a visual sequence from top left to bottom right, it shows the complete evolution process of the ammunition being gradually allocated to each storage facility. color that precisely corresponds to the depot to which it has been assigned. The coloring depth of all nodes reaches a

(iv)Stage 4: The algorithm converges and all ammunition nodes have been assigned, with each node being given a distinct maximum value of 3, indicating that all conflicts have been successfully resolved and each munition has been safely and appropriately assigned to its corresponding storage depot.

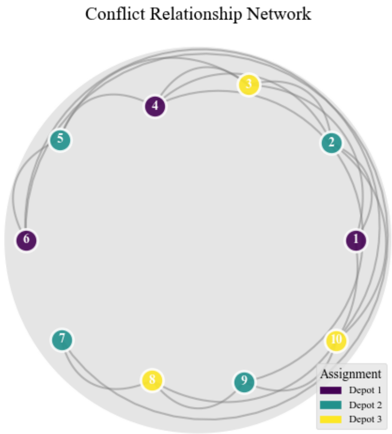

Figure 5 Polar coordinate network diagram

In Fig.5 the purple nodes are assigned to depot 1, yellow nodes are assigned to depot 2, and color nodes are assigned to depot 3. The connecting line indicates that there is a conflict between the two munitions (they cannot be stored in the same depot). Nodes of different colors indicate munitions that are assigned to different depots. It is possible to visualize the conflict relationship and the allocation scheme , effectively satisfying all predefined conflict constraints. In terms of graph theory, this represents a successful graph coloring where no two adjacent vertices (conflicting munition types) share the same color (being assigned to the same depot). This optimized allocation scheme minimizes the possibility of dangerous interactions and ensures compliance with safety protocols.

4. Result Analysis

This section provides an in-depth analysis of the solution results of the optimal ammunition-depot distribution model based on graph coloring theory. The effectiveness, efficiency, and current limitations of the proposed method are comprehensively assessed by describing the heat map of the reordered conflict matrix, the convergence curve during the iteration process of the algorithm, and the depot load distribution map.

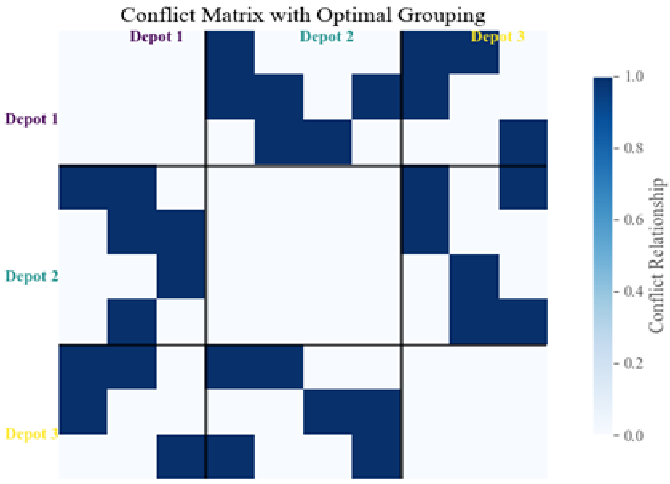

Figure 6 Conflict Matrix Heat Map

4.1 Resolution of ammunition conflict relations and safe distribution

The heat map of the reordered conflict matrix visualizes the model's superior ability to resolve conflicts where munitions do not coexist. The blue areas in Figure 6 clearly indicate the conflict relationships that exist between munition types, while the light-colored areas represent that they can coexist. Through algorithmic optimization, the black lines in the graph clearly group munitions effectively according to their final assigned depots.

There are no predefined conflicts between any of the munition types assigned to the same repository. This not only minimizes potentially hazardous interactions, but also ensures that co-located storage of munitions within each assigned repository is feasible and safe.

4.2 Analysis of Algorithm Convergence and Load Balancing Properties

The blue curve on the left side of Fig. 7 shows that the “number of assigned munitions” grows smoothly and almost linearly with the increase of “algorithm steps”, and finally reaches the maximum value successfully. This trend clearly shows that the proposed graph coloring algorithm has good convergence in solving the ammunition-store allocation problem. It is able to gradually and efficiently assign all the ammunition types to the corresponding depots, ensuring the completeness of the assignment task. The smoothness of the curves further implies that the algorithm avoids violent oscillations or stagnation during the solution process, reflecting its stability and efficiency in the convergence path.

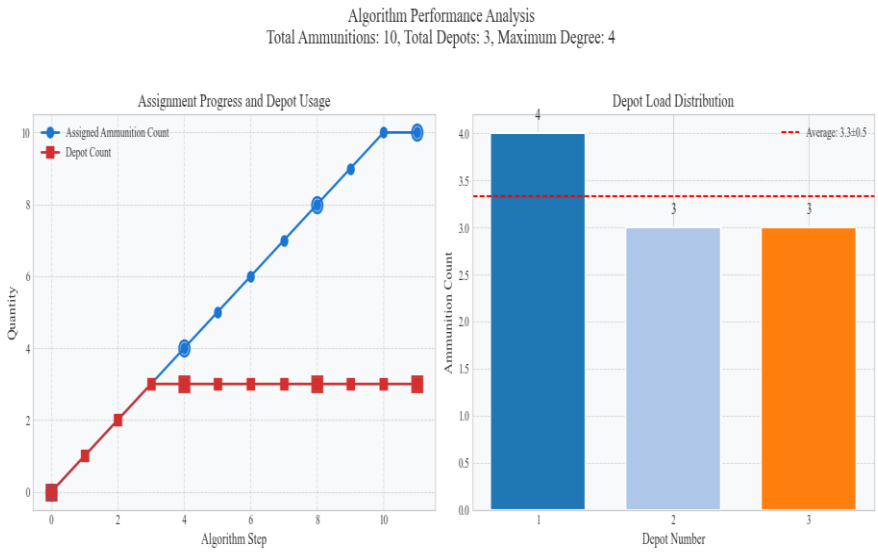

Figure 7 Algorithm convergence and load balancing analysis plot

The load distribution of each depot presented on the right side in Fig. 7, on the other hand, reveals a significant limitation of the current model - load imbalance. The figure clearly shows that the load of depot 1 is significantly higher than that of depots 2 and 3. The number of projectiles in depot 1 is close to 40, while the loads of the other depots are much lower, even below the average load (shown by the red dotted line, about 3.5 units). This significant difference suggests that while the model successfully solves the conflict constraint and minimizes the number of depots, it does not adequately account for load balancing across depots.

This load imbalance can present a range of potential risks in the actual operational context. An over-reliance on a small number of highly loaded depots increases the risk of a single point of failure of those depots in the event of an enemy strike, which, if compromised, could result in the interruption of the supply of large quantities of munitions, severely reducing the operational resilience of the force.

Long-term load imbalance may lead to over-utilization of resources in some depots while others are idle or inefficient, which is not conducive to the optimal allocation and management of overall resources.

5. Conclusion

This study is dedicated to solving the core challenge of insufficient ammunition storage and supply resilience of field ammunition depots in the face of potential enemy threats in the current context of informationized warfare. By treating the ammunition-depot allocation problem as a Boxing with Conflict Constraints (BBPC) problem and introducing the graph coloring theory, it provides a new perspective on the optimal allocation of ammunition.

Combining the efficient data structures in graph theory, the study successfully transforms the non-coexistence relationship between ammunition types into the edges of the graph, thus realizing the optimal allocation of ammunition under strict conflict constraints. The heat map clearly demonstrates that all conflict constraints are strictly adhered to, ensuring absolute safety and compatibility of ammunition storage in each depot. The algorithm shows good convergence during the iterative process, and is able to smoothly and efficiently assign all munitions types to their respective depots, effectively minimizing the number of depots required.

However, the study also reveals an important limitation of the current model: there is a significant imbalance in depot loading. Although the model successfully resolves conflicts and reduces depot usage, some depots have much higher ammunition storage capacity than others. In real-world operations, this could increase the risk of a single point of failure in highly loaded depots, thereby affecting the overall resilience of supply assurance. Future research will focus on solving the load balancing problem and further optimizing the algorithms to achieve a more uniform distribution of depot loads, thus significantly enhancing the destruction resistance and battlefield survivability of the ammunition supply and assurance system.

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