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Wartime Logistics Model for Multi-support Unit Location-Allocation with Front Line Changes

전시상황에서 전선 변화에 관한 복수 군수지원부대 위치 및 물자 수송량 결정 문제

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지도 교수 문 일 경

이 논문을 공학석사 학위논문으로 제출함

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Abstracts

Wartime Logistics Model for Multi-support Unit Location-Allocation with Front Line Changes

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To reflect a realistic, changing front line, wartime logistics are illustrated by a dynamic location-allocation model. In this thesis, a mixed integer programming model is developed to decide the timing of unit relocation for continuous resupply, safe locations for support units, and delivery amounts that minimize total risk to the logistics service. Total risk in wartime logistics is represented by unsatisfied demand, hazard of support site, and the number of relocation. The proposed mixed integer programming model reflects realistic factors in battle situations, such as maximum distance, vehicle capacity, basic load carried by combat units, and limited supplies during unit relocation. Furthermore, special operators for crossover and mutation are developed to maintain feasibility of possible solutions, and an efficient hybrid genetic algorithm is proposed to find optimal and near-optimal solutions.

Keywords: Dynamic location-allocation problem; Hybrid genetic algorithm, HGA; Mixed-integer programming, MIP; Wartime logistics system

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1. Introduction

Security of line of communications (LOCs) and delivery of continuous supplies are recognized as important factors in wartime success. The supply chain of the ROK (Republic of Korea) Army features a multi-level structure that reserves inventory for emergencies, such as during isolation or urgent deployment. Military commodities are classified into 9 categories such as food, ammunition, maintenance item, and so forth. One type of commodity with similar attributes, which is defined as a *class*, has different priority of transport. Army logistics structure is a hierarchical organization consisting of supply and transportation, maintenance, and ammunition. Materials in one type of class may be handled by more than two support units, and a support unit may transport materials of more than one class. Support units analyze previous logistics requirements, estimate current demand, and deliver materials. Combat units in engagement require resupply and relocation to advantageous sites for taking the initiative as situations progress.

To supply at the proper time, in the correct place, and with appropriate quantity is an integral part of success in wartime logistics. The main decision involves the timing of relocation to block risks to increased LOCs, the determination of a relocation site that reduces risk from enemy threats, and the delivery amount of supplies that satisfy daily demand. Support units need flexibility to maintain successive supply operations by keeping reserves and adjusting daily supplies based on uncertainties in the battlefield. Front line changes and damage to friendly forces are the main causes of uncertainties in wartime logistics and can lead to problems in establishing future operations. Uncertainties in the battlefield result from difficulties in predicting an enemy attack. The location of combat units and the demand for supplies change with the levels of enemy hostility. Thus, commanders of support units must consider many factors when deciding when and where to relocate to establish continuous supply operations.

Two approaches are suggested to solve the logistics unit relocation problem. First, flexible responses of support unit toward hazards increase unit responsiveness and thereby preserve possibilities for sustainable logistics services. Second, reserves held for the combat unit can be used to counter unpredictable wartime situations; however, the unit must exercise caution and not hold excessive inventory that may need to be moved expeditiously.

To evaluate the performance of a military logistics services, the geographical advantages of possible locations of support units as well as the service levels necessary to meet demand should be analyzed simultaneously. Thus, the focus of this paper is on a location-allocation problem in which the optimal location and delivery schedule are determined at the same time. The proposed model, which considers evaluation factors, could be practical deciding the time of unit relocation, the location that minimizes risk from enemy threats, and deliver amounts that maximizes the service levels of a wartime logistics support system. The optimal supply system suggested in this thesis might be a scientific decision tool for commanders to make decisions quickly

Figure 1 illustrates a wartime logistics system. In the Cartesian coordinate system, each unit locates at each point. Distances between two units are calculated by Euclidean method. Length of one large square consisting of 5×5 small squares is assumed as one, and the maximum transportable distance is twice the length of one large square. Lines with arrows represent the maximum transportable distance in period 1, and the support unit can deliver materials to combat units without violating the distance restriction of period 1. With the movement of combat units in periods 2 and 3, the support unit must relocate to supply materials within the operational area. A conservative approach is to relocate whenever the distance restriction is violated, which occurs when the second position is candidate node 1 and the third position is candidate node 3. This conservative approach, used with frequent relocations, may translate to fewer enemy threats, but it incurs high relocation and penalty costs. If the support unit moves to candidate node 2 in period 2, it does not need to relocate in period 3. Based on the system shown in Figure 1, the main decisions include timing of the relocation, finding the safest location, and ensuring the proper delivery amount to maximize the effectiveness of the logistics system.

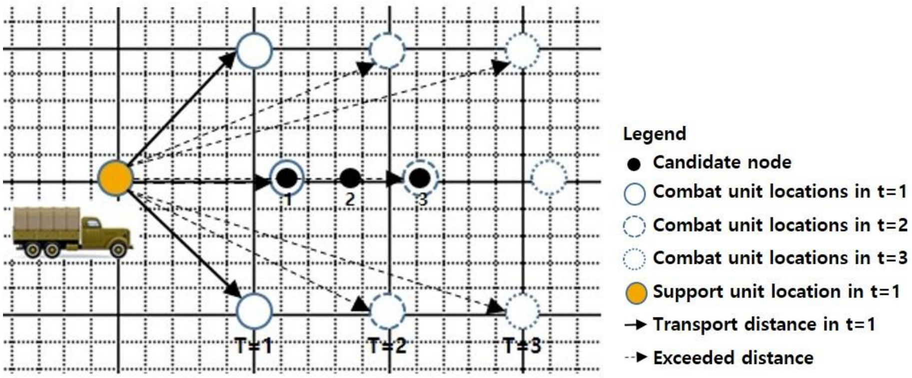

Figure 1 Concept of wartime logistics system

Although the location problem is widely studied, it is difficult to adopt location theory commonly addressed in the private sector to military sector because of the special characteristics of wartime. For example, in war situations, a logistics system that does not impede the operational plan is more important than the cost considerations associated with it.

Especially in the rapidly changing battlefield, commanders must assess the situation quickly and all demands of the combat units must be satisfied to ensure victory. For example, unit locations must be changed frequently due to enemy attacks, and demands depend on the damage to combat units. Generally, at the division level, support units relocate their bases as the command post moves. The commander of the support unit has the authority to decide delivery amounts and transportation modes. Real time analysis of operational areas and wargames are usually good methods to decide the optimal location of support units. Using a scientific-based decision aid, such as the proposed model described in this thesis, the credibility of a logistics plan can be enhanced.

The purpose of this thesis is to establish a wartime logistics model compatible with practical considerations. Basic load, which is defined as the quantity a moving unit must accommodate, is considered so that maximum vehicle capacity and maximum distance are used to illustrate the real environment of wartime. In this thesis, the sequential locations of support units and the delivery schedule in each period are determined. Maximizing the effectiveness of the system can be interpreted as minimizing the total risk to the entire operational system. Risk to combat units is related to unsatisfied demand, and risk to the support unit is related to the hazards inherent in the support site and delays in service during relocation. Unsatisfied demand, resulting from insufficient vehicle capacity, is defined as a shortage of commodities to satisfy demand at the end of each period. The distance from the front line to support units includes the hazard imposed by enemy threats. Thus, location of support units affects all logistics services.

Limits negatively affecting relocation may reduce the delivery amount and result in unsatisfied demand. In this thesis, the logistics service in a dynamic battlefield is described with realistic constraints, and a mathematical model is proposed that minimizes the total costs related to penalties, hazards, and relocation operations. The proposed model determines the timing of the relocation, the optimal location (fewer hazards from enemy threat), and the delivery schedule that minimizes unsatisfied demand. The mathematical model is developed by mixed integer programming (MIP), and a hybrid genetic algorithm (HGA) is proposed to support timely decisions for commanders.

In the next section, research about the location-allocation problem is summarized and the contribution of this thesis is presented. Section 3 features a descriptions of the military logistics service system and establishes the MIP formulation. A genetic algorithm (GA) combined with an efficient heuristic approach, to guarantee higher performance with an optimal and a near-optimal solution, is presented in Section 4. The computational results of the branch and cut method and the HGA are compared and the performance of the HGA is explained in Section 5. In the last section, conclusions about the experiments and suggestions for further research in military logistics are offered.

2. Literature Review

2.1 Location Problem and Supply Chain

Location theory has been studied since 1909 and has flourished through the mid-1960s (Owen & Daskin, 1998). Many researchers have considered the location problem as a strategic decision and produced vibrant research to achieve important results in static and deterministic studies.

Currently, the uncertainty of the real-world challenges the longstanding solutions to the location problem. A few researchers have focused on addressing modern complications. Owen and Daskin (1998) reviewed related studies over a decade and classified the location problem into deterministic, dynamic, stochastic location problems. The deterministic location problem, an area widely studied, is represented by the median, covering, and center problems. Researchers have also investigated other deterministic problems, including fixed charge location, uncapacitated location, capacitated location, and location-allocation problems. The dynamic location problem is used to consider uncertainties of the real-world for long-term and strategic decisions, such as those associated with changing market demands, to locate a facility. Ballou (1968) claimed that the combination of the optimal location in each period guarantees the highest benefit for long periods while accounting for changes in the market.

From this foothold, Wesolowsky (1973) added the concept of cost for relocation, and Hormozi and Khumawala (1996) used a mixed integer programming with dynamic programming to generate a guaranteed optimal solution. Stochastic location problems are used to consider uncertainties of demand and distance, which few researchers have addressed with the distribution and scenario planning approaches.

Melo, Nickel, and Saldanha-da-Gama (2009) studied location problems that included supply chains, and they pointed out that only 20% of 120 research studies addressed the uncertainties of demand and distance. They suggested that more researchers focus on uncertainties of the market, which is an important aspect of the problem. Aghezzaf (2005) proposed robust optimization to solve uncertainties in a multi-period situation. Melo et al. (2009) emphasized six classification factors to be considered in the location problem: capacity, inventory, procurement, production, routing, and transportation mode. A few researchers studied capacity and inventory at the same time. Routing is an important factor for the distribution network as well. Perl and Daskin (1985), and Lee, Moon, and Park (2010) solved location routing problems in supply chain network design. Considerations of routing in the location problem can make the system more realistic for problems involving military logistics, where the size of the echelon affects the routing factor. At the division level of the logistics system, the routing schedule may not be able to accommodate a large delivery amount that is urgently needed in a wartime situation. Company level logistics can be appropriately considered in the context of the location routing problem because it involves only one truck for multiple delivery schedules.

Many initial studies about the dynamic location problem were based on dynamic programming. However, combining each optimal solution does not guarantee an optimal solution over all periods. Therefore, many researchers have developed heuristic approaches, including those that integrate a mixed integer with dynamic programming and a GA. Jaramillo et al. (2002) compared the performance of a GA for different types of location problems. They showed that the GA for the capacitated facility location problem gives an optimal solution but over a long computational time. Beasley and Chu (1996) adopted a GA to address the set-covering problem and suggested a solution that increases feasibility; that is, they applied penalty function to a heuristic operator. Deb (2000) showed that the GA is a good method for a combinatorial problem, summarized five ways to handle constraints, and suggested an efficient heuristic method for handling these constraints. Imposing a penalty cost for a violation of constraints requires a credible parameter.

In this thesis, the MIP model contains realistic constraints, for which feasible solutions are difficult to find with the procedures used in a GA. Thus, it is important to understand the entire structure of the GA and develop special genetic operators. Constraints in the MIP model are related to capacity, distance, and inventory. A multi-period problem is complex because genetic operators, such as crossover and mutation, are applied in each period. Thus, understanding all the structure of constraints is the most important starting point to ensure feasibility. Abdelmaguid and Dessouky (2006) suggested ways to retain feasibility during crossover and mutation operations for the integrated inventory distribution problem. Kim (2004) suggested a GA with a positive integer for the location problem. The research presented in this paper is based on a combination of Abdelmaguid and Dessouky's (2006) and Kim's (2004) techniques as they apply to information on a delivery schedule and the location of support units.

2.2 Military Logistics Support System

Many researchers have shown that, for the military logistics support system, maximizing total effectiveness to guarantee success is more appropriate than the common approach of reducing total distribution costs. The second best solution, which is more expensive than the best one, could be chosen for a future operation. Continuous resupply at all costs is of utmost importance to a successful war effort, and it is more important than saving money but interrupting supply delivery. For example, an infantry battalion in a reconstitution situation might be supplied by air so it can be deployed promptly. In other words, at least for wartime logistics, to maximize effectiveness for victory is typically the most significant goal of any solution to a problem.

Malhotra and Jain (2002) showed that the weapon location problem is studied widely in the wartime areas of battle management / command, control, and communications. Levin and Friedman (1982) maximized total effectiveness to establish the deployment plan of support units. They assumed that three main factors affect the effectiveness of wartime logistics services: how close the support units are to combat units, the safety of the support unit location, and how much effort was required to occupy the current location. Gue (2003) proposed a location and material flow model for Sea-Based Logistics (SBL) with the objective of minimizing the inventory of moving units; however, the situations of the ROK Army are different from those of SBL; for example, the ROK may need to reserve a certain level of inventory for the land-based operations needed to overcome an emergency. Lee, Lee, and Moon (2013) developed several SBL vehicle scheduling models to minimize exposure to the enemy.

Location problems in military applications have been studied in two areas: warehouse location in peace time and weapon location-allocation in wartime. Sim, Jang, Jung, and Jeong (2013) summarized the differences between the military supply chain and the private supply chain using characteristics of military logistics. The environment of military logistics system applies to an integrated logistics system. Adapting to the changing environment, they suggested that the mathematical formulation be used to determine the optimal location and the number of facilities to open. Farahani and Asgari (2007) considered multi-attributes of candidate sites to find optimal locations. Kim (2004) studied the uncapacitated multi-support unit location problem with dynamic programming and a genetic algorithm.

2.3 Contributions

The difference of this thesis from those of researchers in the private sector is the time horizon. In many private sector problems, the decisions on where to locate a warehouse or the number to operate are based on a long-term need. However, battlefields must be relocated frequently regardless of the cost incurred; that is, it is a special location-allocation problem. Many studies from the private sector are too limited and cannot be adopted in the military sector, which has distinct characteristics. Although the dynamic facility location problem deals with the changing market, changes in wartime happen very fast, and the fixed cost to relocate units is small compared to that of plant relocation. Thus, a specialized location model is required to design a wartime logistics system.

The study presented herein can be classified as a dynamic capacitated facility location-allocation problem. The proposed model simultaneously determines the timing for relocating support units, the site with fewest enemy threats, and the appropriate delivery amount based on wartime circumstances.

Sridharan (1995) indicated that a capacitated plant location problem deals with limited capacity. For the study described in this paper, the support units are assumed to have sufficient inventory to cover all demands, and vehicle capacity depends on the type of commodities and the status of support units (either stationary or moving). To describe a wartime logistics system in a practical way, realistic constraints are added.

Each support unit manages multiple types of items and each commodity has an assigned priority in the supply. One item can be delivered by multiple support units, which allows direct delivery from high echelons. The Forward Supply System (FSS) describes support units that use their own vehicles and is used in this thesis. FSS is a general distribution method for military logistics except in emergencies which support units are not mission capable under enemy attacks. Limited supply is considered to curtail transportable capacity during relocation is undertaken. A material balance equation and an inventory boundary that describe basic loads for combatants are also used. Damages to combat units affect the priority of resupply. Table 1 summarizes the research related to this thesis.

Table 1 Summary of relevant papers

Author(s) (year)	Location problem	Transport volume allocation	Customer (combat unit)		Commodity			Multi period	Routing	Maximum capacity	Limited capacity during relocation
			Basic load	Damage	Multi	Overlap supplier	Priority				
Levin and Friedman (1982)	√										
Gue (2003)	√	√	√		√		√	√		√	
Lee et al. (2013)		√			√		√	√		√	
Sim et al. (2013)	√	√			√			√		√	
Kim (2004)	√						√	√			
Ballou (1968)								√			
Murty and Djang (1998)	√								√		
This thesis	√	√	√	√	√	√	√	√		√	√

3. Mathematical Model

3.1 Problem Description

This thesis simultaneously determines the sequential locations of support units and the schedules used to deliver materials; it is classified as a multi-period, multi-commodities, multi-support unit location-allocation problem. Each support unit transports commodities every combat unit. A support unit relocates to another site according to distance restrictions. With the assumption that locations and demands of combat units are known, the timing of relocation, the safe location of support units, and the delivery amount in each period are decided. Although the assumption might be unrealistic, operations could be conducted with the analysis of operational areas and enemy threats by intelligence staffs. The assumption, which demands and locations of combat units in short period can be predicted, could be complemented by updating current situations in rolling horizon so that commanders assess wartime situations quickly and make prompt decisions. The maximum distance, maximum vehicle capacity, and basic loads of combatants are practical constraints. The objective is to minimize total costs related to penalty, relocation, and hazard. To define relationship among penalty, relocation, and hazard, the cost minimization approach is used; however, the total costs are to define weights for each type of through experiments.

3.2 Assumptions

The battlefield is described with a graph consists of combat units, support units, and routes. Units locate at nodes and vehicles travel on arcs. Only one unit can be located at one node. Candidate sites for support units have many attributes to be considered, but distance from the support base to the combat units is the only factor taken into account in this paper.

1) Initial locations of combat and support units are already determined, the front line is changed according to battlefield situations, and support units relocate their positions to new sites to deliver materials. Locations and demands of combat units in the short term can be predicted.

2) Military commodities are classified into *m* categories and include food, ammunition, and maintenance items. Each support unit manages several items within the same group of commodities, which have similar attributes. Two supports units can manage the same item.

3) Each support unit has sufficient quantities to satisfy daily demand and transports items with its own vehicles (FSS). Combat units cannot hold excessive inventory; they carry only the basic load.

4) Relocation creates fixed costs related to the characteristics of the support units. Because troops use their own vehicles while relocating a base, a limited supply rule is adopted during relocation, which means that the transportable capacity is reduced during relocation.

5) Unsatisfied demand results from limited vehicle capacity and a limited supply rule during relocation.

6) The hazard of candidate sites linearly decreases with increased distance from the front line.

The time horizon consists of three characteristics. In the beginning of each period, combat unit deployment is completed so troops are ready to fight. The support unit checks the distance from its base to each combat unit location to decide whether to relocate the current base or to transport supplies without relocating. Combat units receive supplies within each period, then check the unsatisfied demand, and move to another location to resume operations on the next day.

3.3 Notations

This thesis develops an MIP model for a dynamic capacitated multi-support unit location-allocation problem using the following notations.

Indices

i, j : index of arbitrary node$(i, j = 1,2, \ldots, N_t)$

s : index of support units $(s = 1,2, \ldots, S)$

c : index of combat units $(c = 1,2, \ldots, C)$

k : index of commodity $(k = 1,2, \ldots, K_s)$

t : index of periods $(t = 1,2, \ldots, T)$

Sets

N_t : set of candidate nodes for support units in period t

S : set of support units

C : set of combat units

K_s : set of commodities for each support unit s

T : set of time periods

Parameters

N_{cnt} : 0-1 matrix to represent location of combat unit c for all nodes n over all periods

D_{ckt} : demand of commodity k for combat unit c in period t

d_{ij} : distance from node i to node j

$maxD$: maximum transportable distance for support unit s per period

$maxI_{ck}$: maximum inventory of commodity k for combat unit c

C_{sk} : maximum capacity of support unit s to transport commodity k

E_h : weight for hazard cost

E_c : weight for priority to supply resulted from the damage of combat unit c

E_r : weight for relocation cost of support unit s

∂_k : weight of commodity k

b : required capacity during relocation (e.g., %)

Decision Variables

x_{sckt} Amount of commodity k transported from support unit s to combat unit c in period t

z_{sit} 1, if support unit s decides to be located at node i in period t
0, otherwise

U_{ckt} Unsatisfied demand of commodity k for combat unit c in period t

R_{st} 1, if support unit s is stationed at the same node from period *t-1* to t
0, otherwise

I_{ckt} Inventory of commodity k for combat unit c at the end of period t (the initial inventory, I_{ck0} is given)

The objective function consists of a penalty, a relocation, and a hazard cost. The penalty cost results from the unsatisfied demand of each period. The relocation cost is a fixed charge for different types of support units moving bases in period *t-1* to another site in period *t*. The hazard cost is used to find a less hazardous site, which is far from the front line.

To minimize

$$\sum_t \sum_s \sum_c \sum_k E_c \times U_{sckt} + \sum_t \sum_s E_r \times (1 - R_{st}) + \sum_t \sum_s \sum_c \sum_i \sum_j E_h \times Z_{sit} \times \frac{N_{cjt}}{d_{ij}} \quad (1)$$

Constraints

Subject to

$$I_{ckt} = I_{ck,t-1} + \sum_{s \in S} x_{sckt} - D_{ckt} + U_{ckt} - U_{ck,t-1}$$
$$\forall\, c,\ \forall\, k,\ \forall\, t \quad (2)$$

$$\textstyle\sum_c x_{sckt} \le C_{sk} \qquad \forall s,\ \forall k,\ \forall t \quad (3)$$

$$\textstyle\sum_{i \in N_t} z_{sit} = 1 \qquad \forall s,\ \forall t \quad (4)$$

$$\textstyle\sum_{s \in S} z_{sit} \le 1 \qquad \forall i \in N_t, \forall t \quad (5)$$

$$\textstyle\sum_{s \in S} z_{sit} + \sum_{c \in C} N_{cit} \le 1 \qquad \forall i \in N_t, \forall t \quad (6)$$

$$\textstyle\sum_{i \in N_t} \sum_{j \in N} (Z_{sit} \times N_{cjt} \times d_{ij}) \le maxD \qquad \forall s,\ \forall c,\ \forall t \quad (7)$$

$$z_{sit} - z_{si,t-1} \le 1 - R_{st} \qquad \forall s,\ \forall i,\ \forall t \quad (8)$$

$$\textstyle\sum_{c \in C} x_{sckt} \le C_{sk} \times (R_{st} + b) \qquad \forall s,\ \forall k,\ \forall t \quad (9)$$

$$\partial_k \times I_{ckt} \le \max I_{ck} \qquad \forall c,\ \forall k, \forall t \quad (10)$$

$$X_{sckt},\ U_{ckt},\ I_{ckt} \ge 0, \text{ integers} \qquad \forall s, \forall\, c,\ \forall\, k,\ \forall\, t \quad (11)$$

$$Z_{sit},\ R_{st} \in \{0,\ 1\} \qquad \forall s, \forall i \in N_t, \forall t \quad (12)$$

Constraint (2) refers to inventory balance equations. Constraint (3) indicates that the number of commodities transported should be less than the maximum vehicle capacity. Constraints (4), (5), and (6) restrict the unit such that only one can be located at one node and all the support units are on the graph over all periods. A support unit locates at a node within the boundary of maximum distance as indicated by Constraint (7). Constraint (8) restricts the number of relocations. The objective function includes the relocation cost, and this model finds the location of support units such that unnecessary relocations are reduced. Constraint (9) limits the vehicle capacity for transport during a relocation. Constraint (10) suggests that the basic load of combatants restricts the amount of commodities held for combat units

3.4 Sample Case

Small size problem presented by Kim (2004) is the recent study about ROK Army logistics model in wartime. An instance is adopted from the small size problem to verify the proposed model. With increasing total number of nodes (N) in the operational area, the number of candidate nodes for support units (N_t) increases. Total number of nodes (N) in the small size problem is ten, which is very small case but meaningful when the total supply operation is easily understood by tracing the sequential location of support units over all planning periods. Although the experimental setting is different from the original example, both models return the sequential locations of a support unit. Starting from the comparison of both models about the simple case, this thesis develops realistic combat scenario in experiments to verify the proposed model. Input data about demand, distance, and location of combat units over all periods are the same between the two experiments, but an additional factor is required to describe the proposed model. Table 2 shows the input data.

The wartime logistics system consists of two combat units with an inventory boundary of 100 items and includes one support unit with one type of commodity. All combat units hold 20 items of initial inventory. A support unit uses its own vehicles with 100 items of capacity to transport materials. Combat units move and receive deliveries every day. The damage rate of each combat unit is 1 and 2. The planning horizon is 3 days.

Table 2 Input data for sample case

Factors		t_1	t_2	t_3
Demand	c_1	16	73	95
	c_2	24	86	75
Combat unit location	c_1	3	4	8
	c_2	5	6	10

Input data	Value
I_{ck0}	20
$maxD$	13
b	0.6
$maxC$	100

As shown in Table 3, the optimum solutions avoids frequent relocations and finds the timing of each relocation as related to maximum distance. In addition to this, the proposed model determines delivery amounts with minimum unsatisfied demands. The original experiment (Kim, 2004) assumes that all demands are satisfied because of no restrictions for vehicle capacity. For example, if distances between the support unit and each combat unit in period 2 do not exceed the maximum distance, the support unit stays at the current position and delivers materials at full capacity. In period 3, the distance between units exceeds the maximum distance, so the support unit relocates to node 6 and delivers materials with their limited capacity vehicles. Because the damage rate of combat unit 2 is higher than combat unit 1, combat unit 2 is the priority for supplies. This model considers material flow with the maximum vehicle capacity and the limited supply rule. Credible results of the location and delivery amount related to the timing of relocation can be achieved.

Table 3 Comparison of results between example cases

Factors	Previous research (Kim, 2004)			This thesis		
Support unit location	1 → 3 → 6			1 → 1 → 6		
Delivery amount	t_1	t_2	t_3	t_1	t_2	t_3
	16	73	95	0	69	26
	24	86	75	100	31	34

4. Hybrid Genetic Algorithm

While the real-world problem can be described by a mathematical formulation, increasing the problem size affects the computation time. For wartime logistics, which require urgent decisions for successful operations, another approach applicable for a combinatorial problem needs to be considered.

A GA is based on the survival of the fittest as characterized in nature; that is, the chromosome that evolves in a way that maximizes its ability to endure the environment survives. Starting from an initial chromosome of randomly determined characteristics, each generation is produced to create the desired population size, and the fitness of each chromosome is evaluated. The fittest chromosomes are chosen through selection and became parents for the next generation.

Crossover is a main technique of the GA to search the neighborhood of possible characteristics among chromosomes and to capture the best characteristics of parents to pass to their offspring. Mutation is conducted to introduce new features in a parent by replacing selected information points in a single parent chromosome with different information.

Although the performance of GA to search solutions is great, the procedure did not always guarantee possible solutions. The characteristics of the proposed algorithm, which includes practical constraints, make it difficult to maintain feasibility of solutions. In this thesis, there are five types of decision variables important to the outcome: delivery amount, location of support units, unsatisfied demand, timing of relocation, and inventory of combat units. Delivery amount and location of support units are decided, and the number of relocations should be minimized by the objective. There are constraints to be considered while proceeding with the GA: maximum distance, vehicle capacity, and basic load. To solve this dynamic location-allocation problem with constraints, heuristic approaches are used to find feasible solutions. A heuristic is used to generate initial solutions and develop genetic operators.

Based on the technique of Abdelmaguid and Dessouky's (2006), which suggested two approaches to handle capacity constraint violations, procedures to adjust delivery amount are adopted. Kim's (2004) technique to represent the information of unit location is used in the procedure of GA. Because the proposed algorithm includes different types of information in chromosome, the combination of techniques to handle constraints and find sequential unit location is required.

4.1 Genetic Representation

In this thesis, the chromosome has multiple components that include information on delivery schedule, support unit location, timing of relocation, unsatisfied demand, and holding inventory of combat units. All components in the chromosome should be initiated because of their important characteristics. The support unit location and the delivery schedule are decisive components, and the other types of information are dependent components. The decisive component is determined mainly to diversify the characteristics through crossover and mutation. To maintain feasibility and satisfy constraints, dependent components should be adjusted according to the decisive component in each procedure.

Chromosome length is determined by the number of variables it contains. Figure 2 shows the optimal solution of a sample case. The solution is encoded into a genetic form and includes delivery schedule, support unit location, unsatisfied demand, timing of relocation, and holding inventory. Each component is transformed into special forms for the crossover and mutation procedures. Then, all components are connected in series to represent the general form of a chromosome.

x_{sckt}						Z_{sit}												U_{ckt}						R_{st}			I_{ckt}					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
4	96	100	0	60	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	69	0	1	1	0	4	96	0	41	0	0

Figure 2 Genetic representation

To describe a specific representation of each component in a chromosome, the sample case featured in Section 3.4 is used. Figure 3 describes each type of information included in the chromosome. In this case, the delivery schedule is two-dimensional with 2 rows and 3 columns. Each cell in the matrix represents the delivery amount of commodity *k* from support unit *s* to combat unit *c* in each period. The support unit location is represented by cells arrayed in 2 rows and 12 columns. The column shows the candidate node in each period. The first row represents the set of candidate nodes in each period, and the length of each row represents the total number of candidate nodes over the periods. The second row shows the location of the support unit in each period. For the case of multi-support units, an integer value is used to represent the location of each support unit. For unsatisfied demand and inventory, the row shows the number of combat units and commodities, and the columns represent the planning horizon. The timing of relocation is reflected in the information on the support unit in the single row.

(a)

Type of information	t_1	t_2	t_3
$s_1k_1c_1$	4	100	60
$s_1k_1c_2$	96	0	0

(b)

Type of information	t_1		t_2			t_3						
N_t	1	2	1	2	3	1	2	3	4	5	6	7
Z_{sit}	1	0	1	0	0	0	0	0	0	0	1	0

(c)

Type of information	t_1	t_2	t_3
k_1c_1	0	0	69
k_1c_2	0	0	0

(d)

Type of information	t_1	t_2	t_3
s_1	1	1	0

(e)

Type of information	t_1	t_2	t_3
k_1c_1	4	0	0
k_1c_2	96	41	0

Figure 3 Genetic representation of each information type in the sample case: (a) delivery amount from the support unit to each combat unit; (b) sequential locations of the support unit; (c) unsatisfied demands of combat unit; (d) the timing of the support unit relocation; (e) the inventory of each combat unit

4.2 Initialization

The procedure to generate an initial solution for the GA follows. Figures 4 and 5 are flowcharts that represent the process used to produce an initial random solution based on the greedy algorithm. The procedure starts with determining the distance between units, then it proceeds to either transporting materials with full capacity or relocating the support unit position. Figure 4 shows the flowchart of the main problem for initialization. Figure 5 shows the sub-problem (SUB) that is used if the distance between the support unit and all combat units exceeds the maximum distance. The SUB finds an alternative location and appropriate delivery amounts.

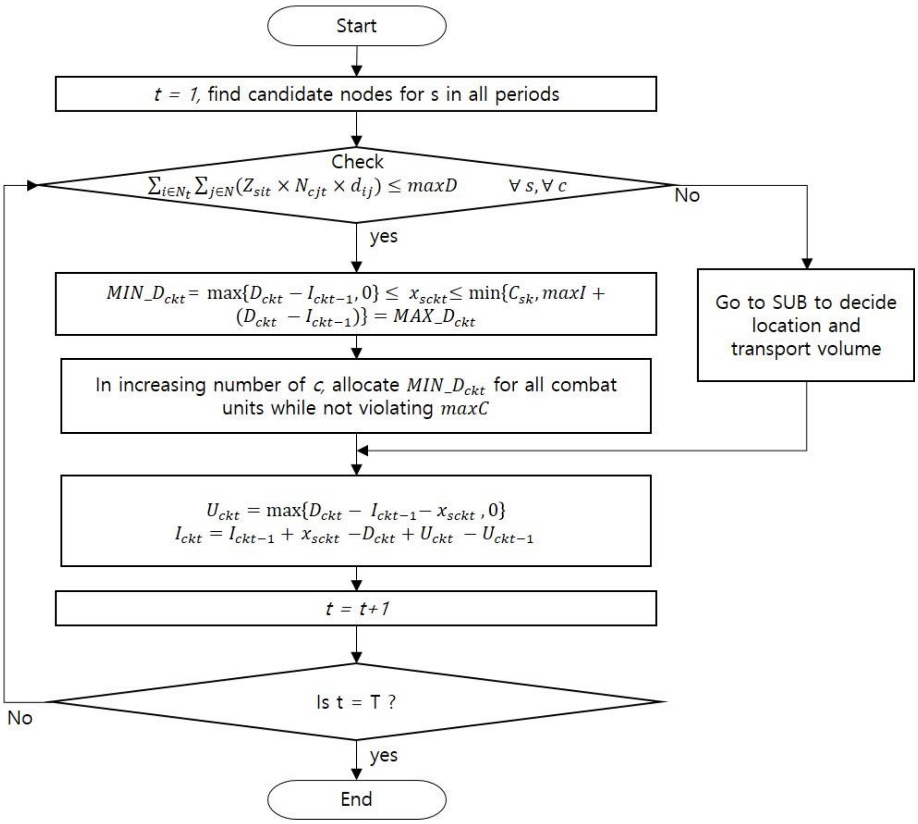

Figure 4 Flowchart of the main problem for genetic algorithm initialization

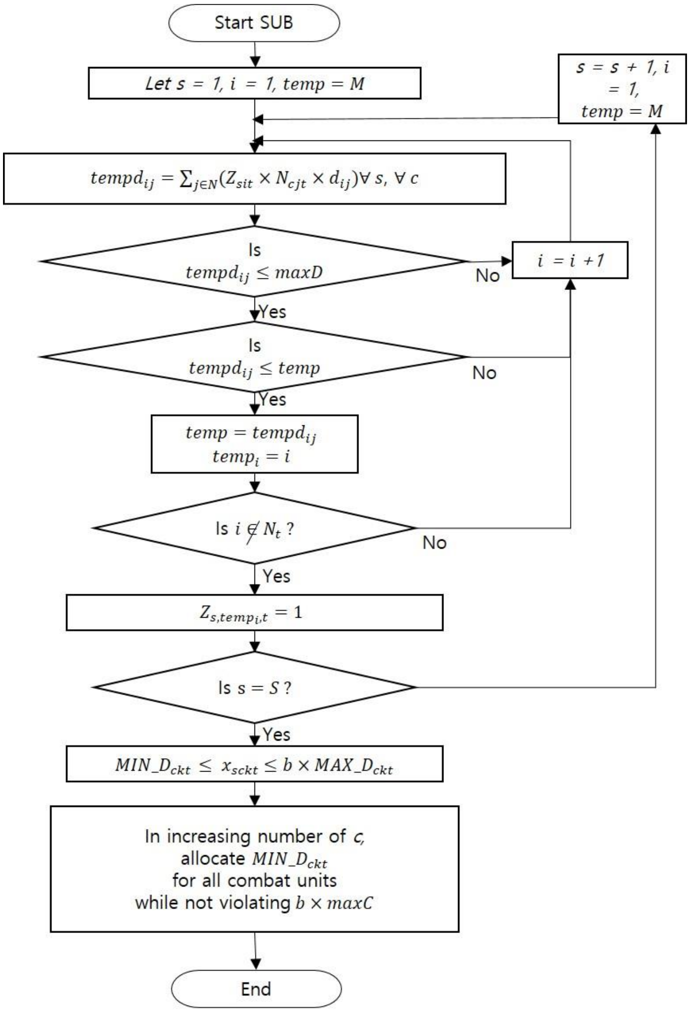

Figure 5 Flowchart of the sub-problem used for initialization of the genetic algorithm

4.3 Selection Operator

A chromosome is selected in a random process through a roulette-wheel. The selector determines and evaluates the fitness of each chromosome in the beginning of each generation and chooses chromosomes through a probability based on fitness. The following fitness equation is based on the quality of proportionality method. It returns the fitness of the best chromosome that is *k* times higher than the fitness value of the worst chromosome. Generally, *k* is an integer between 2 and 4, which controls the selective pressure. At a higher value of *k*, the gap between the probability of choosing a superior chromosome and that of choosing an inferior chromosome increases. The fitness function is as follows:

$$fit_i = C_w - C_i + \frac{(C_w - C_b)}{(k - 1)} , \qquad k > 1$$

C_w: The worst total cost in the population

C_b : The best total cost in the population

C_i : The total cost of the i^{th} population

4.4 Crossover Operator

4.4.1 Crossover for the delivery schedule

Abdelmaguid and Dessouky (2006) proposed an appropriate GA for the integrated inventory-distribution problem. They designed a crossover operator rule to maintain feasibility. Vertical breakdown arranges the delivery schedule of each period. Horizontal breakdown adjusts the delivery schedule of the selected combat unit over periods. In this thesis, by curtailing unsatisfied demand and adjusting the delivery amount, the horizontal break down is adopted to reduce unsatisfied demand. The delivery schedule for each combat unit will be exchanged, which may cause the vehicle capacity to be violated. Maximum transport capacity changes according to the relocation information. The remaining capacity should be kept through crossover procedures to maintain feasibility. Then, a vertical breakdown is used for specific periods in which the capacity constraint has been violated. This procedure reduces the violation of the capacity constraint and combines fitter features of parents to produce relatively evolved offspring. The steps to maintain feasibility are as follows:

Step 1: Exchange a randomly selected row and check the remaining capacity.

Step 2: Find the vehicle capacity constraint violations, and conduct horizontal breakdown for the selected row.

Step 2-1: Adjust the current delivery to satisfy the maximum vehicle capacity and check the unsatisfied demand for each period.

Step 2-2: Adjust the delivery amount in the previous periods to minimize unsatisfied demand.

Step 3: If the remaining capacity < 0, then conduct a vertical breakdown.

Step 3-1: Adjust the delivery amount for other combat units in this period.

Step 4: Adjust unsatisfied demand and inventory according to the decisive component.

Figure 6 shows the crossover procedure for the delivery schedule for the sample case. The sample case is too small to show all crossover steps included in the vertical breakdown. However, the proposed procedure outlined in step 3 can be adopted for large problems.

Step 1

P1	t_1	t_2	t_3
x_{111}	16	50	60
x_{112}	24	50	0
Remaining vehicle capacity	60	0	0

P2	t_1	t_2	t_3
x_{111}	16	73	60
x_{112}	24	27	0
Remaining vehicle capacity	60	0	0

Step 2

O1	t_1	t_2	t_3
x_{111}	16	50	60
x_{112}	24	27	0
Remaining vehicle capacity	60	23	0

O2	t_1	t_2	t_3
x_{111}	16	73	60
x_{112}	24	50	0
Remaining vehicle capacity	60	-23	0

Step 2-1

O1	t_1	t_2	t_3
x_{111}	16	50	60
x_{112}	24	50	0
U_{21}	0	36	75
Remaining vehicle capacity	60	0	0

O2	t_1	t_2	t_3
x_{111}	16	73	60
x_{112}	24	27	0
U_{21}	0	59	75
Remaining vehicle capacity	60	0	0

Step 2-2

O1	t_1	t_2	t_3
x_{111}	16	50	60
x_{112}	84	50	0
U_{21}	0	36	15
Remaining vehicle capacity	0	0	0

O2	t_1	t_2	t_3
x_{111}	16	73	60
x_{112}	84	27	0
U_{21}	0	0	74
Remaining vehicle capacity	0	0	0

Figure 6 Crossover for the delivery component when dealing with vehicle capacity violation

4.4.2 Crossover for location

For support unit location, an order crossover which Davis (1985) designed for the permutation type of chromosome, is used. Procedures of order crossover are illustrated in Figure 7 and outlined as follows:

Step 1: Select two points in each period at random.

Step 2: Generate offspring by copying the element of parent between two points into the same position of it.

Step 3: Fill the element of the other parent from the second point into the temporary offspring in the order of candidate node. Delete the elements that are already in the offspring.

Step 4: Place the elements from the next position of the second point according to the order of candidate node.

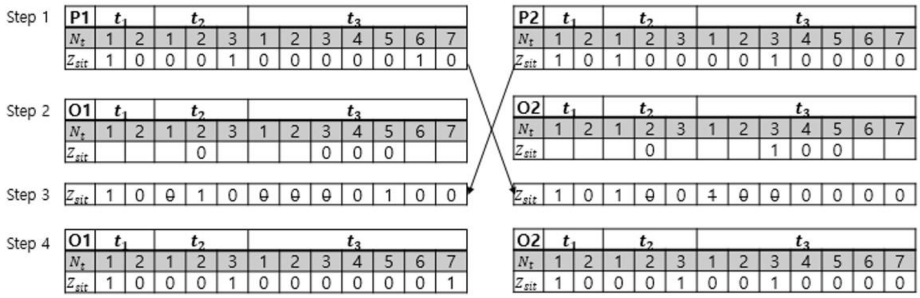

Figure 7 Order crossover for the location component

4.5 Mutation Operator

Mutation is conducted according to the types of information in the chromosome. The main factor in deciding the quality of the chromosome is the location of support units because the transportable capacity changes based on information related to relocation. Thus, the mutation is directed at the location information portion of the chromosome to remove unnecessary relocations.

First, choose two points in each period. One point should contain the node occupied by a support unit, and the other point should represent an unallocated candidate node. Then, swap the element at each points selected point in each period so that the number of relocations is reduced and fewer hazardous locations are found. The more possible solutions that a candidate node is changed is associated with a greater possibility that a nonhazardous location is identified. Then, the timing of relocation is adjusted. Second, the transportable and remaining vehicle capacity for transport is calculated. Changes to transportable capacity may generate vehicle capacity violations. In cases of vehicle capacity violations, procedures described in Section 4.4.1 are adopted to maintain feasibility through adjustments of current delivery, delivery amounts in previous periods, and delivery amounts to other combat units in the current period. For example, if 40% of total vehicles are assumed to be used during relocation, only 60% of total maximum capacity of materials can be transported in the relocation period. In this situation, vertical and horizontal breakdowns are used to satisfy the limited supply rule while minimizing unsatisfied demand. Last, unsatisfied demands and inventory information are adjusted. Figure 8 shows the procedure for introducing mutations in the sample case.

Step 1

O1	t_1		t_2			t_3						
N_t	1	2	1	2	3	1	2	3	4	5	6	7
Z_{sit}	1	0	1	0	0	0	0	0	0	0	0	1

⇨

O1	t_1		t_2			t_3						
N_t	1	2	1	2	3	1	2	3	4	5	6	7
Z_{sit}	1	0	0	1	0	0	0	0	0	0	1	0

Step 2

O1	t_1	t_2	t_3
$s_1k_1c_1$	16	73	60
$s_1k_1c_2$	80	27	0
Remaining vehicle capacity	4	-40	0

⇨

t_1	t_2	t_3
16	73	60
80	0	0
4	-13	0

⇨

t_1	t_2	t_3
16	64	60
84	0	0
0	0	0

Figure 8 Mutation procedure to maintain feasibility for the sample case

5. Computational Experiments

The MIP models in Section 3 were coded using XPRESS 7.7 on a PC with an Intel® Core™ i5-3470 CPU of 3.20 GHz and 8GB RAM. System features 32 MB of RAM and Intel Pentium. The proposed GA was programmed using MATLAB R2014b.

To enhance the reliability of the experiments, input data for demand were created using the daily requirement featured in Beddoes (1997), who studied SBL, which has been useful for comparing different characteristics of combat units. The rifle company described by Beddoes is similar to the infantry unit in this thesis. The Beddoes light armored reconnaissance platoon is like an armored platoon, and the AAAV platoon is like a fleet of tanks. Table 4 shows daily demands for combat units.

Table 4 Daily demands for combat units

Combat unit	**Class 1**		**Class 3 (Fuel)**	**Class 5 (Ammo)**
	(Food)	**(Water)**		
Infantry company	806	7,644	230	842
Armored platoon	154	1,470	3,430	2,243
Tank platoon	205	1,974	14,280	3,259

These input data are meaningful for considering different characteristics of combat units, which consist of infantry, armor, artillery, and so forth. Daily demand varies depending on the characteristics of each combat unit. For example, armored units require fewer supplies for personnel, but more parts to repair mobility equipment because they have less personnel than infantry units. Many researchers studying multi-commodities in military logistics assume that each support unit handles one type of commodity and the number of support units is identical to the number of classes. However, in reality, nine different types of classes are grouped and managed together. One type of class has various goods. For example, class 1 features as rice, rations, and water. Although fuel is classified as a class 3 commodity, classes 1 and 3 are managed by the same support unit. Class 5 is used to describe all types of ammunitions in the army. In emergencies, ammunition delivery is given a higher priority than goods in other classes. In other words, each support unit handles several different classes and each class is uniquely prioritized. This thesis handles a multi-commodity situation, which means that one support unit handles several types of classes consisting of various items.

Two experiments are conducted to evaluate the performance of the MIP model and the HGA. Experiment 1 defines credible parameters with restrictions on pre-delivery to find relocation timing when demand is relatively small. Experiment 2 allows for pre-delivery, which encourages holding inventory of basic load for combat units.

Unit movements and resupply are performed within the operational area. Combat units occupy new locations to seize initiatives under enemy attacks and locations of combat units define the front line in each period. Support unit commanders make many decisions for continuous resupply based on front line changes. For example, the commander of the support unit must decide the timing of relocation, the safest location from enemy attack, and the delivery amount in each period. Support units should not proceed to the front line ahead of combat units. Engaged combat units might have a high damage and require urgent deliveries of supplies to make repairs. Some types of commodities should be supplied immediately such as ammunitions. Combat units can hold maximum inventory, defined as basic load, for mobility. Support units are assumed to have same number of vehicles up to the number of combat units. The operation rate of vehicles remains at 85% as some are assumed down for maintenance. The type of commodities determines the type of vehicles needed; for example, an oil-tanker is needed for class 3, and a truck delivers class 5 goods. The maximum capacity differs by vehicle type.

5.1 Experiment 1

A battlefield consists of 40 nodes, 2 support units, 3 types of commodities (food, oil, and ammunition), and 5 combat units (3 infantry, 1 armor, and 1 artillery). The duration of operations is 30 days, sequential locations of combat units over the periods are shown in Table 5. Distances between nodes are calculated using Euclidean distance. Demands are generated randomly, within a 10% gap, based on data in Table 4. Each combat unit moves at the beginning of each period, and each support unit decides whether to deliver or relocate.

Table 5 Sequential locations of combat units

Combat unit	Sequential locations of combat units
c_1	7→13→21→26→29→32→37
c_2	8→10→12→20→27→31→34→36→39
c_3	9→11→17→22→25→28→30→33→35→38→40
c_4	6→8→10→18→24→27→31
c_5	5→9→11→17→22→25→28→30

One support unit manages food and oil, and another support unit handles ammunition. In experiment 1, the relationship between the coefficient for the relocation cost, E_r, and the coefficient for the hazard, E_h, is tested. Support units have sufficient vehicle capacity to deliver materials to meet for all demands except in emergency cases such as when urgent resupply for combat units is not mission capable for the support unit. Thus, the mathematical model finds the optimal delivery amount by transporting materials in advance to deal with emergency cases. Pre-delivery for an emergency is restricted to compare the correlation values of the coefficients. Table 6 shows the results of experiment 1 as completed with Xpress using the heuristic option. The Xpress searches solutions based on branch and cut algorithm and cuts. The number of combat units and the maximum distance are fixed.

Table 6 Comparison of results in experiment 1

Case	s	c	k			N	E_r			E_h	Sum of total costs	Relocation cost	Hazard cost	Penalty cost	Number of relocations
			s_1	s_2	s_3		s_1	s_2	s_3						
1	2	5	①②	③	-	40	500	1000	-	10^3	12429	3000	6694	2735	4
2	2	5	①②	③	-	80	500	1000	-	10^3	12245	3000	6510	2735	4
3	2	5	①②	③	-	120	500	1000	-	10^3	11864	3000	6283	2580	4
4	3	5	①	②	③	40	500	500	1000	10^3	16526	4000	9970	2555	6
5	3	5	①②	③	②	40	500	500	1000	10^3	13970	4000	9970	0	6
6	2	5	①②	③	-	40	500	1000	-	4×10^3	32233	4000	24949	3284	5
7	2	5	①②	③	-	40	500	1000	-	9×10^3	63353	4500	54668	4185	6

Cases 1, 2 and 3 show that increasing the number of nodes encourages support units to find locations with fewer enemy threats, which results in a decreased total cost. In Case 3, for example, the penalty cost as well as the hazard cost are decreased. Two approaches are used to decide the timing of a relocation with restricted of pre-deliveries. Table 7 shows the mathematical model for the optimal timing in situations of relatively low demand so that the total logistics system incurs a minimum penalty cost.

Table 7 Two approaches to finding the timing of relocation

Support unit	Timing of relocation						Optimal sequential location		
	Conservative			Optimal					
s_1	1	9	22	1	9	20	1(t_1)	7(t_9)	18(t_{20})
s_2	1	13	26	1	13	26	2(t_1)	8(t_{13})	19(t_{26})

The MIP model yields the optimal timing of relocation because of the demand levels of each period. The type of commodity with a shortage is type ②, which is managed by s_1. Vehicle capacity for type ② is 29,750, and it is 17,850 during relocation. The optimal sequential location suggests that the best timing for relocation of s_1 is t_{20}, but distances between units exceed the maximum distance in t_{22}. Demand for type ② in t_{20} is 25,910, it is 26,249 for t_{21}, and it is 27,604 for t_{22}. Table 8 shows how this model decides the timing of relocation.

Table 8 Demand and delivery amount in each period

Combat unit	Demand			Delivery amount		
	t_{20}	t_{21}	t_{22}	t_{20}	t_{21}	t_{22}
c_1	6948	8156	7923	6948	8156	7923
c_2	7814	6895	8049	7814	6895	8049
c_3	7544	7575	8039	0	2799	1878
c_4	1457	1474	1554	1457	0	0
c_5	2147	2149	2039	1631	0	0
sum	25910	26249	27604	17850	17850	17850
$U_{c,2,t}$	0	0	0	8060	8300	9745

A conservative solution for relocation timing is found when the distances between units exceed the maximum distance. In this problem, location at t_{22} makes up the conservative solution, but it corresponds to a relatively high unsatisfied demand. The optimal solution, relocating in advance, minimizes unsatisfied demand. The model finds the timing of relocation with low demand to minimize penalty cost.

Case 5 in Table 6 shows that support unit 3, which handles type ②, reduces unsatisfied demands. Support unit 3 can be considered an additional supplier in a high echelon. Cases 1, 6, and 7 show that changes in coefficients E_r and E_h affect the number of relocations. Table 9 shows a sensitivity analysis for parameters E_r and E_h. Figure 9 illustrates the result of the sensitivity analysis. The larger the ratio of E_r to E_h, the more frequently support units relocate. Because the objective function is used to minimize total cost of the logistics service, the model finds safe locations, but relocations should be done such that E_h is four times bigger than E_r. The number of relocations and the limited supply rule affect future operations, and the parameters in cases 1-5 result in fewer relocations being adopted for the experiment 2.

Table 9 Sensitivity analysis for parameters

E_r	E_h ($\times 10^3$)										
	2	4	6	8	10	12	14	16	17	18	20
1000	4	5	5	5	5	5	5	5	6	6	6
1500	4	4	4	5	5	5	5	5	5	6	6
3000	4	4	4	4	5	5	5	5	5	5	5

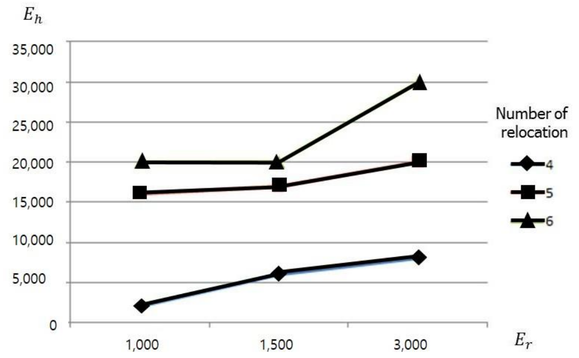

Figure 9 Relationship of coefficients for the number of relocations

5.2 Experiment 2

For the practical experiment, delivery in advance is allowed. E_r and E_h from cases 1 to 5 of experiment 1 are adopted to minimize the number of relocation. The following experiments are conducted by increasing the number of support units, nodes, and overlapping suppliers. Table 10 shows the computation results as completed with Xpress.

Table 10 Computation results of experiment 2 by Xpress

Case	Support unit	Combat unit	Type	Node	Sum of total costs	Relocation cost	Hazard cost	Penalty cost	Computation time(s)
1	2	5	3(1:1:1)	40	9538.26	3000	6538.26	0	10.9
2	2	5	3(1:1:1)	80	9353.92	3000	6353.92	0	75.3
3	2	5	3(1:1:1)	120	9251.87	3000	6251.87	0	155.3
4	3	5	3(1:1:1)	40	13970.43	4000	9970.43	0	18.8
5	3	5	3(1:1:1)	80	13784.79	4000	9784.79	0	419.9
6	3	5	3(1:1:1)	120	13694.88	4000	9894.88	0	67435.0
7	3	5	3(1:2:1)	40	13970.43	4000	9970.43	0	14.1
8	3	5	3(1:2:1)	80	13784.79	4000	9784.79	0	2771.4
9	3	5	3(1:2:1)	120	13677.72	4000	9677.72	0	7464.0

The XPRESS tends to find an optimal solution that minimizes total cost; it reduces penalty cost by allowing for delivery materials in advance, hazard cost by locating support units at safe nodes, and relocation cost by adjusting the timing of relocation. For the size of experiment 2 with allowance of pre-delivery, the optimization model finds a delivery schedule with no unsatisfied demand. Because the delivery schedule is adjusted by holding inventory for combat units, the XPRESS can take the conservative approach which guarantees a low hazard cost by keeping the current location of support units as long as possible. Table 10 shows that the number of nodes and support units increase the complexity of the problem because of the increased combinations of locations; however, the number of supplier types and the rate of overlapping suppliers does not affect in the computation time because the support unit is assumed to have sufficient capacity to transport different commodities to combat units. For example, in case 6, the XPRESS only finds feasible solutions in an 18 hour computation time, which are worse than the best solution of HGA. Most of the results from the XPRESS model reflect optimal solutions, but it takes more computation time for such a large problem.

Although the MIP model depicts wartime logistics with practical constraints and the XPRESS finds optimal solutions, wartime logistics requires urgent decisions and credible solutions must be found as soon as possible so that commanders can make important decisions quickly. Battlefield situations change frequently, so that belated decisions are useless. Thus, the efficient heuristic algorithm is required for wartime logistics of a practical size. The HGA finds the optimal and near-optimal solution in a relatively short time by searching neighborhoods. The proposed HGA was developed by accounting for the characteristics of the decision variables, and special genetic operators were proposed to find feasible solutions in every evolutionary situations.

Table 11 **c**ompares results from the XPRESS, which is conducted by branch and cut approach to find solutions, and the HGA. In most cases, the HGA finds the optimal solution in the shortest time. Optimal solutions of the HGA are verified by visualizing the locations of support units and comparing delivery amounts with those features determined by the XPRESS. As the size of a problem increases, the computation time of the

XPRESS also increases, but the HGA can find optimal and near-optimal solutions within 40 seconds. In the HGA, the population size is 100, and termination is complete when either the optimal solution is found or the near-optimal solution (within a 1% gap) is determined, or the generation size is 100. For this thesis, the convergence of the HGA is rapid from the beginning, and little gap emerged by the 10th generation.

Table 11 Comparison results of the branch and cut algorithm and the hybrid genetic algorithm

case	s	c	k			Node	Branch and cut			HGA		Gap
			s_1	s_2	s_3		Sum of total costs		Computation time(s)	Sum of total costs	Computation time(s)	
1	2	5	①②	③	-	40	9538.26	Optimal	10.9	9538.26	25.84	Optimal
2	2	5	①②	③	-	80	9353.92	Optimal	75.3	9353.92	24.50	Optimal
3	2	5	①②	③	-	120	9251.87	Optimal	155.3	9251.87	29.82	Optimal
4	3	5	①	②	③	40	13970.43	Optimal	18.8	13970.43	29.05	Optimal
5	3	5	①	②	③	80	13784.79	Optimal	419.9	13784.79	30.28	Optimal
6	3	5	①	②	③	120	13694.88	Feasible	67435.0	13684.03	31.75	-
7	3	5	①②	③	②	40	13970.43	Optimal	14.1	13970.43	25.89	Optimal
8	3	5	①②	③	②	80	13784.79	Optimal	2771.4	13784.79	28.19	Optimal
9	3	5	①②	③	②	120	13677.72	Optimal	7464.0	13684.00	28.95	0.99

The result for the sequential location of support units in case 1 is illustrated in Figure 10. Parameters are based on case 1 described in Section 5.1: two support units, five combat units, three types of commodities, and 30 days of operation. As the front line changes, two support units decide the timing of relocation in a conservative way as described in Section 5.1. Sequential locations of support units are 1 → 7 → 18, 2 → 8 → 19.

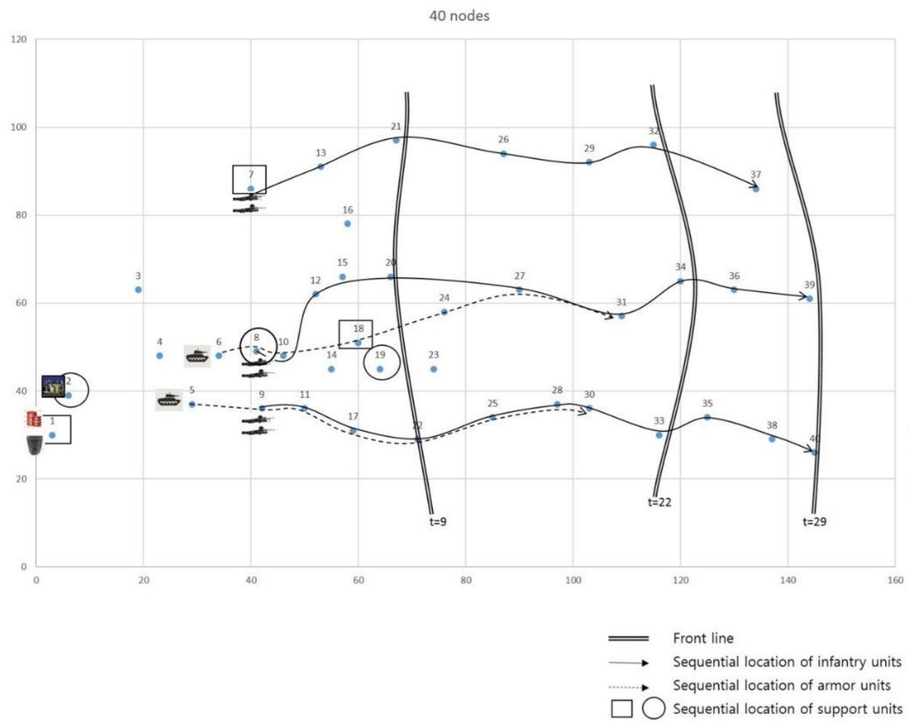

Figure 10 Visualized result for the location of support units

For case 6, the MIP model could not find the optimal solution, and the HGA could find a better solution in less computation time. The HGA could find solutions quickly by using an efficient heuristic in every generations. For small problems, initial solutions are generated based on the greedy algorithm and a 2% or smaller gap from the optimal solution is found. For large problems, the fitness of the initial solution is poor. By initiating genetic operators, the performance of the HGA improves. By searching the set of candidate nodes and crossover, the HGA moves support units to the next location and thus guarantees fewer hazards. Crossover for the delivery amount is conducted by choosing a row that demonstrates unsatisfied demand such that feasible solutions, which do not violate the vehicle capacity restriction, survive to the next generation. The proposed HGA allocates the delivery amount in each period by adjusting the current delivery amount, the delivery amount in the previous period, and the delivery amount for multiple combat units in the current period. Mutations for locations are conducted to find more safe locations for support units. In these procedures, the HGA finds solutions at a higher level of performance than the MIP model does.

6. Conclusion

A multi-support unit location-allocation model in wartime is described in this thesis. Realistic constraints, such as the maximum distance, the maximum vehicle capacity, the limited supply rule effected during relocation, and the basic load for combatants were considered. The MIP model was proposed to minimize the total cost related to unsatisfied demand, relocation, and hazard. A division level of logistics model was conducted with the assumption that demands and locations of combat units in future operations were predictable. The result showed that the wartime logistics could be easily solved by a mathematical model and suggested optimal solutions for the supply plan.

Furthermore, an HGA for wartime logistics was developed for commanders to estimate situations and make decisions quickly. The GA was combined with an effective heuristic algorithms to find feasible solutions quickly. In less computational time than taken by branch and cut procedures in Xpress, the proposed HGA for wartime logistics suggested the optimal and near-optimal solutions for the timing of relocations, delivery amounts, and safe locations.

Although input data were not based on real training data, the credibility for experiments were created through the adoption of daily requirements from previous research (Beddoes, 1997) and the illustration of the wartime logistics environment. A sample case was tested as a modified version of previous research (Kim, 2004) to verify the optimal solution generated by the mathematical model. The locations and demands of combat units were assumed known, but in reality, the battlefield is characterized by uncertainties due to enemy attack. Thus, expanding this thesis to a stochastic allocation problem using Xpress would be an interesting research area. In addition, the probability that enemy threats from rear area operations might be higher than the assumption of hazard rate for candidate sites. Thus, a simulation model of wartime logistics with stochastic demands and enemy threats could offer a visualized decision tool that commanders could use to deal with uncertainties. As the heuristic algorithm using initialization procedure in GA finds good initial solutions for small size problem, improving the heuristic algorithm without adopting procedures in GA might suggest better performance to find solutions for the proposed model. With various practical combat scenarios, the proposed model could be used in supply operations.

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초 록

전시상황에서 전선 변화에 관한 복수 군수지원부대 위치 및 물자 수송량 결정 문제

이 연구는 전선이 변화하는 상황에서 병참선 신장을 막기 위해 군수지원부대 위치결정 및 할당문제를 다룬다. 지속적인 보급을 위한 군수지원부대의 재배치 시기를 판단, 적의 위협에 대비한 안전한 위치 확보 및 군수지원시스템의 위험도를 최소화하기 위한 수송량을 결정하는 문제를 혼합정수계획법을 이용한 수리모형으로 제시하였다. 전시 군수지원의 총 위험도는 미충족 수요량, 군수지원지점의 위험도, 그리고 재배치 횟수로 대표된다. 제시된 수리모형은 차량 용량, 수송가능거리, 전투부대 휴대 가능량, 재배치 간 제한적 수송 등 현실적인 제약상황을 다루었다. 제약조건을 위배하지 않으면서 가능해를 구하기 위한 교차 및 변이 연산이 적용되었고, 최단시간내 최적해 및 최적근사해를 구하는 혼합유전알고리즘을 이용하여 지휘관이 신속하게 의사결정을 하는데 도움이 되는 모델을 개발하였다

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