Methodological Approach To And Modeling Of The Use Of Robots In The Eradication Of Mined Zones

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METHODOLOGICAL APPROACH TO AND MODELING OF THE USE OF ROBOTS IN THE ERADICATION OF MINED ZONES
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Abstract

This paper presents an alternative solution to eradicate zones containing antipersonnel mines by using robots. The solution involves two stages whereby the supply chain of the robots used is strategically optimized. This serves as the basis for a tactical solution of the problem through the dynamic planning of resources.

The strategic model is an adaptation of the previews proposals. A new formulation is added to the chain’s tactical model, which includes linear variables and fractional restrictions; the solution procedure takes advantage of the monotonicity of the objective function. Finally, the models are used to study the Colombian case.

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1 Introduction

Mine-laying is a common practice in war conflicts due to the low cost and easiness of construction of antipersonnel mines (at least in low sophisticated devices). In the army, mines are used differently: to block the advance of the enemy into a specific area; to gather the enemies in areas where they can be easily attacked; to obstruct their movements during attacks; to prevent them from using resources in areas that will be abandoned (natural resources, facilities, equipment, communication routes, etc.). Mines can also be used to reinforce natural or artificial obstacles; to prevent enemy retreat, to facilitate military retreat, and to get in the way of the enemy’s logistic support.

Mines have meant another issue in the horror of war because of the damage they cause to civilians. The main reasons are, on the one hand, that landmine-laying and mine-clearance dynamics are hardly predictable and carelessly registered, and therefore, impossible be analyze; on the other hand, that partial mine-clearing of fields, also known as 'gap opening' in the military jargon, is a general practice.

The consequences of mine explosions are burns, multiple wounds and infections caused by splinters. Wounds may have deadly consequences due to the very impact or to the evolution of the injuries received. Besides, there is constant fear amongst the affected population because of the risk of danger they are exposed to.

The 2003 annual mine report suggests that antipersonnel mines killed 300,000 people in the whole world in 2002. The number of mutilated people in Angola is considered to be around 20,000 according
to the United Nations, and 70,000 according to Doctors without Borders’ reports. For a population of 10 million people, the rate could be from 1 out of 500 inhabitants to 1 out of 145. In Somalia, the approximate rate is 1 out of 650 and in Cambodia 1 out of 234. In Colombia, the number increased from 216 in 2001 to 530 in 2002, and between January and April of 2003, 151 casualties and wounded people were reported.

The Red Cross International Committee (RCIC) estimates that 800 people die monthly (26 per day) due to mines, while figures from the U.S. Department of State speak of 26,000 casualties and wounded people per year (72 per day). According to estimations published in IDOC Internazionale, for each victim surviving to a mine explosion, two people die. In some countries, 75% of the survivors require amputations.

Numbers are difficult to calculate since most highly-mined countries (with a recently ended conflict or still in conflict) lack the necessary infrastructure to act and to look after the victims on time.

Using data from the Physicians for Human Rights organization (PHR) as a reference, medical treatment costs to guarantee full recovery are between US$3,000 and US$5,000, while costs of the equipment needed by a child victim are over US$3,000.

The United Nations’ rejection to use antipersonnel mines as war devices (as a consequence of the devastating impact on worldwide population, where victims are mostly people not involved in the conflict) is registered in the 1997 Ottawa Convention. The commitment of several countries was looked for to eradicate minefields in a period no longer than 10 years. The results of the Ottawa Convention motivated this project, and established the time and the dynamic nature of the mine-clearing problem.
Among the measures agreed in the Convention are: the establishment of observation centers to identify mined zones, the promotion of the necessary measures to eradicate mines, a ban on the production and use of mines as weapons by governments, and the elimination of mine provision. The traditional mine-clearance process is first done from a distance; minefields are made to explode with projectiles launched from airplanes and helicopters, or with artillery; the fields are then swept with hand detectors by specialized personnel. Due to the varied characteristics of mines and of laying mechanisms, the mine-clearance process is far from being effective, safe and ecological.

As a result of the technological progress made, robots seem to be as a new possibility for mine-detection. Although the progress made is not enough for a massive implementation, it can be foreseen that this possibility will increase specialized personnel security and decrease mines’ harmful impact on the environment. Future massive use of these devices will depend on the benefit-cost relation, and on whether interested parties are willing to adopt the technological advances that guarantee robots’ adequate performance.

The future feasibility of this option led us to propose the mine-clearance project here presented. The proposal includes the technical conditions and dynamics of robot production; other logistic aspects, such as location, transportation and distribution of the necessary infrastructure for implementation, are also considered.

The project is divided in two parts: a strategic one concerning location and allocation (including the scope of the study), and a tactic one (annual dynamics) dealing with the production, transportation, and distribution planning.
2 Background

Facilities, location, and allocation are key elements for the success of the operation of any manufacturing process or service due to the final costs it may generate. A wrong location may hamper distribution and lead to the accumulation of raw materials, products in process, or finished products; it may cause an overload in material handling systems, inefficient production processes, and long lines. All this may finally generate economic loss and customer dissatisfaction. Inadequate assignment of the product chain to stores and then to customers can make worthless all production efforts to offer an excellent product in terms of quality and cost, as well as the marketing efforts to make an efficient operation. Thus, good decisions concerning facilities’ location and allocation in a supply chain contribute to the operation’s total efficiency.

The mathematical programming used in the optimization of domestic supply chains is usually based on the optimization of an objective performance measure: the reduction of operation costs or the maximization of operation utilities. Reference works include NP complete whole mixed programming solved using the Branch and Bound algorithm. Khumawala (1972) suggests a first approximation to the problem; Geofrion and Graves (1974), and Geofrion, Graves and Lee (1978) qualify the location problem, and restrict each facility to be supplied by one single store (something logistically advisable in most cases); the authors propose the use of Benders’ acceleration method to reach the solution. Pooley (1984) expands the qualified problem by adding a plant location stage and the assignment of plants to distribution centers; however, the author does not mention the algorithm used for the solution. A non-qualified approach is presented by Balou (1984), who sets forth the non linear optimization of inventory costs and proposes a solution algorithm that, according to the author, guarantees a local minimum. Finally Vidal and Goetschalckx (2000), include the effect on uncertainties on global logistics systems mainly supplier reliability.
On the other hand, the tactical and operational aspects involved in a supply chain emerge as a later consequence of the strategy, whereby physical and organizational networks are established and decisions are made in a limited period of time. Among the necessary considerations are: the bill of material, raw material inventories, in-process and finished products, and transportation and distribution assignments; the purpose is to minimize costs of production, transportation, distribution and inventories or to maximize operational utilities. Geoffion and Powers (1995) review in detail the evolution of supply chain modeling.


3 Definition of the problem

The topology of plants’ and distribution centers’ location depends, to a large extent, on the particular conditions imposed by military policies concerning safety, manufacturing autonomy and monopoly, and war material distribution.
The army is made up of divisions which are subdivided into brigades; these consist of battalions of different kinds: engineering, cavalry, artillery, infantry, elite forces, etc., one of them being the central battalion. Each brigade is in charge of defending a piece of national territory. This kind of organization prevents any possible overlapping among brigades and fosters effective operations and safety.

War material produced by the military industry is distributed among the various divisions; these, in turn, distribute it to brigade’s central battalions, and the latter send it to the rest of the annexed battalions, and from there, to operation zones.

The regulations established by the Ottawa Convention promote the creation of mechanisms to obtain statistics (which are based on the incidents reported by civil population and military groups, and on reports about mined zones) that allow the identification of minefields.

However, the data collected does not allow to calculate robot demand in terms of mine numbers; thus, robot supply is determined not by the number of mines to be detected, but by the area to be covered in a particular period of time. This is because the whole area allegedly containing mines must be swept by robots, regardless of mine density. It is possible to guarantee the area that the robot will cover in a certain period of time, but not the number of mines to be found.

Given the characteristics of the military organization and the demand estimates, it can be concluded that the location problem is restricted to the location of production plants and to the distribution of robots from there to the different brigades’ general battalions where storage and distribution centers will be located.

The transportation of war material is very peculiar; division battalions and brigade headquarters are located in highly-protected cities with various means of transportation, the most common one being
the helicopter. Therefore, military industries, as well as cantons, are usually located in these places.

On the other hand, distribution is more complex since it needs the support of helicopters flying from the brigade’s battalions to war zones and then back to cantons.

Robot manufacturing is modular, that is to say, mechanical and electronic parts are assembled in production cells, and this operation is carried out by pairs of workers.

4 Modeling strategy

The location problem mentioned above arises naturally as a transformation of the facility location model proposed by Pooley (1994). Modifications are of two types: some of them are simplifications since here we are dealing with one single product, the location of distribution centers, and the relaxation of distribution to demanding zones; on the other hand, there is a restriction of demand by store, and one single source of supply from plant to stores.

4.1 Topological Determination of the Production, Storage, Transportation and Distribution Network based on Added Costs

The whole network is restricted to having each center supplied by one single plant or facility. Thus, the model uses average added costs per period for planning. Costs are divided into production, transportation, distribution, and storage costs, plus the fixed costs of implementing plants and distribution centers.
Due to the particular conditions of the problem, the location of distribution centers is assigned to general brigade battalions, as well as the distribution of robots from each center to the corresponding influence zone. The formulation is shown below:

**Notation**

Indexes:
- $i$ = plant index
- $j$ = distribution centers index

**Sets**

- $Q$ = Plants
- $R$ = Distribution centers
- $SPC$ = Logistics Connections between plants and distributions Centers

**Parameters**

- $P_{ci}$ = Production capacity of plant $i$ during planning
- $W_j$ = Storage capacity of distribution center $j$ when planning
- $o$ = Unitary volume of item
- $w$ = Average area covered by a robot per period during planning
- $AA_j$ = Average annual mined area that center $j$ is in charge of during planning
- $d_j = AA_j/w$ : Average demand of distribution center $j$
- $Gv$ = Average capacity of robot transportation by helicopter regarding volume restriction
- $Gp$ = Average capacity of robot transportation by helicopter regarding weight restriction
$G = \text{Average capacity of robot transportation by helicopter. It is established as the minimum between average capacities of volume and weight, that is:}
\[G = \min(G_v, G_p)\]

\textbf{Costs:}

Costs are added during planning
- $e_i = \text{Average fixed cost of plant in site } i \text{ during planning}$
- $f_j = \text{Average fixed cost of distribution center in site } j \text{ when planning}$
- $C_{ij} = \text{Average cost of transportation per unit from plant } i \text{ to distribution center } j \text{ when planning}$
- $v_j = \text{Average variable cost of storage per unit in distribution center } j \text{ when planning}$
- $p_i = \text{Average cost of production per unit in plant } i \text{ when planning}$
- $a_i = \text{Average cost of reparation per unit in plant } i$
- $h_j = \text{Average cost of distribution per unit from distribution center } j \text{ when planning}$

\textbf{Variables}

- $X_{ij} = \text{Average annual number of units produced in plant } i \text{ and transported to distribution center } j$
- $A_i = \text{Binary variable if plant is located in site } i$
- $CC_{ij} = \text{Binary variable if plant } i \text{ supplies distribution center } j$

\textbf{Formulation}

Objective Function:
It is a cost additive function that corresponds to the total of costs involved in the operation. There are six types of costs:
1. Average annual cost of plant installation during the planning period.

2. Average annual cost of production during the planning period.

3. Average annual cost of item transportation from production plants to distribution centers during the planning period.

4. Average annual cost of item storage in distribution centers during the planning period.

5. Average annual cost of item distribution from distribution centers to the demanding area during the planning period.

6. Average annual cost of installation of distribution centers during the planning period.

\[
\text{MinZ} = \sum_i c_i A_i + \sum_{(i,j) \in SPC} p_i X_{ij} + \sum_{(i,j) \in SPC} c_{ij} \left( \text{int} \left( \frac{X_{ij}}{F} \right) + 1 \right) \\
+ \sum_{(i,j) \in SPC} v_{Cij} d_j + \sum_{(i,j) \in SPC} h_j \left( \text{int} \left( \frac{X_{ij}}{F} \right) + 1 \right) \\
+ \sum_j f_j 
\]  

\[(4.1)\]

**Restrictions**

**Restriction to store demand:** It allows annual demands for the item to be satisfied in each distribution center. There are as many
restrictions as distribution centers.

\[ \sum_j X_{ij} \geq \sum_i CC_{ij}d_j \quad j \in R \]  

(4.2)

**Restriction on plant capacity:** Plant production is restricted to its maximum annual capacity. The number of restrictions is the same as the number of plants

\[ \sum_j X_{ij} \leq Pc_iA_i \quad i \in Q \]  

(4.3)

**Restriction to the capacity of Distribution Centers:** The annual storage capacity of each distribution center is restricted to its maximum annual capacity. The number of restrictions corresponds to the number of demand centers.

\[ \sum_i oX_{ij} \leq W_j \quad j \in R \]  

(4.4)

**Mass balance restriction:** This restriction prevents idle stocking of items in distribution centers, so that these are exclusively used to distribute and store the number of items requested. The number of restrictions corresponds to the number of distribution centers.

\[ \sum_i X_{ij} = d_j \quad j \in R \]  

(4.5)

**Restriction to Simple Distribution Source:** This restriction favors the logistic condition of each distribution being done by one single plant. The number of restrictions corresponds to the number of distribution centers.

\[ \sum_i CC_{ij} = 1 \quad j \in R \]  

(4.6)

**Logistic Coherence Restriction:** To support the previous restriction, this one guarantees that if there is a logistic connection between a plant and a distribution center, such plant completely satisfies (with all the items) that center’s demand. The number of restrictions corresponds to the number of plant - distribution center combinations.

\[ X_{ij} = CC_{ij}d_j \quad (i,j) \in SPC \]  

(4.7)
4.2 Determination of the Production, Storage, and Transportation Infrastructure disintegrated during planning

From the first model on, costs are disintegrated in annual periods, so that the planning for each period is a dynamically optimized. Cost division is explained below:

- Variable production costs: raw material, workforce, equipment and machinery costs
- Transportation costs: costs of fuel and trucks
- Distribution costs: costs of fuel and helicopters

The model is shown below:

Indexes:
t = Time
k = Time
i = Plant
j = Distribution center

Sets:
T = Periods
M = Store and Distribution Centers

Constants
Nut = Number of time unist.
N = Periods.
H_{ij} = Distance from manufacturing plant i to storage and distribution centers j.
L_j = Distance from storage and distribution centers j to demanding request zone.
V_j = Percentage demand of robots assigned to storage and distribution center j.
f = Number of available helicopters.
G_v = Average capacity of transportation of robots per helicopter considering volume restriction.
\( G_p \) = Average capacity of transportation of robots per helicopter considering weight restriction.

\( G \) = Average capacity of transportation of robots per helicopter. It is established as the minimum between average capacities of volume and weight.

\( m \) = Percentage of undetectable mines per planning period.

\( l \) = Number of robots that a mine-deactivation expert is in charge of.

\( A \) = Total mined area for the planning period.

\( g \) = Number of robots built by a team in planning period.

\( r \) = Time units of robot maintenance per planning period.

\( a \) = Time units of robot repair.

\( w \) = Area covered by a robot per time units.

\( sh \) = Helicopter flight security factor.

\( V_H \) = Helicopter average speed.

\( X_{\text{max}} \) = Robot production maximum capacity.

\( Y_{\text{max}} \) = Maximum number of pairs of technicians allowed.

\( du \) = Time units of robot construction.

**Variables**

\( X_t \) = Number of robots manufactured in period \( t \).

\( Y_t \) = Number of pairs of technicians employed in period \( t \).

\( I_t \) = Number of helicopters used in period \( t \).

\( e_t \) = Total distance covered by a helicopter for transportation purposes in period \( t \).

Where: \( G = \min(G_v, G_p) \)

\[
e_t = \sum_{j=1}^{M} \frac{L_j V_j X_t}{G} \quad (4.8)
\]

\( d_t \) = Total distance covered by a helicopter in period \( t \) for distribution purposes.

Where: \( G = \min(G_v, G_p) \)

\[
d_t = \sum_{i,j} \frac{H_{ij} V_j X_t}{G} \quad \forall (i, j) \in \text{Red Optima} \quad (4.9)
\]
\[ T_t = \text{Number of helicopters to be bought in period } t. \]

Costs.
Costs are disintegrated per period.
\[ c_t = \text{Robot construction and repairing cost in period } t. \]
\[ p_t = \text{Cost of two technicians in period } t. \]
\[ n_t = \text{Cost of a mine-deactivation expert in period } t. \]
\[ o_t = \text{Transportation cost in period } t. \]
\[ q_t = \text{Distribution cost in period } t. \]
\[ b_t = \text{Cost of one helicopter in period } t. \]
\[ z_t = \text{Cost of equipment for technicians in period } t. \]
\[ f_t = \text{Average cost of robot spare parts in period } t. \]

Objective Function:
This is a cost additive function corresponding to the total of costs involved in project planning. There are seven types of costs:

1. Cost of raw material for item manufacture, depreciation and development costs.
2. Cost of spare parts for damaged robots.
3. Cost associated with the production employees’ salary.
4. Cost of materials and equipment used by employees and associated depreciation.
5. Cost associated to mine-deactivation experts’ salary.
6. Costs of item transportation from plants to distribution centers and depreciation of vehicles.
7. Costs of item transported from distribution centers to demanding zones and depreciation of vehicles.
8. Cost of helicopters that distribute items and their depreciation.
\[
\text{Min } \sum_{t} c_t X_t + \sum_{t=1}^{du} f_t \cdot du \cdot r \cdot m \cdot X_t
\]
\[
+ \sum_{t=1}^{N-du} f_t (N - du - t) \cdot r \cdot m \cdot X_{du+t}
\]
\[
+ \sum_{t} p_t Y_t + \sum_{t} z_{t-1} Y_t + \sum_{t} l \cdot n_t \cdot X_t + \sum_{t} q_t e_t + \sum_{t} o_t d_t
\]
\[
+ \sum_{t} b_t T_t \tag{4.10}
\]

Restriction on added demand: It allows the total demand of land mine-clearance to be satisfied. This restriction takes into account the robots’ life-span. There is only one restriction.

\[
\sum_{t=0}^{du} du(Nut - a \cdot m - r)w(X_{t+1}/2)
\]
\[
+ \sum_{t=1}^{N-du} (N - du - t)(Nut - a \cdot m - r)w(X_{du+t+1}/2) \geq A \tag{4.11}
\]

Restrictions on workforce capacity: It establishes that the number of production teams in an assembly unit is capable of producing and repairing the number of robots needed to satisfy the production commitment.

\[
Y_t = \frac{X_t}{g} + \sum_{k=1}^{t} \frac{X_k \cdot m}{a} \quad t = 1, 2, ..., du \tag{4.12}
\]
\[
Y_t = \frac{X_t}{g} + \sum_{k=1+du}^{t} \frac{X_k \cdot m}{a}
\]
\[
t = du + 1, du + 2, ..., N - du \tag{4.13}
\]
\[
Y_t = \frac{X_t}{g} + \sum_{k=1+N-2du}^{t} \frac{X_k \cdot m}{a}
\]
\[
t = N - du + 1, N - du + 2, ..., N \tag{4.14}
\]
Flight time restriction: It establishes that the number of helicopters used to transport robots must be enough to satisfy requirements when planning.

$$\sum_t \sum_j \frac{L_j V_j X_t}{T_t G} + \sum_t \sum_{i,j} \frac{H_{ij} V_j X_j}{T_t G} \leq 12 \ast N \ast VH \ast sh$$

(4.15)

Restriction on the number of robots: The number of manufactured robots can not exceed a maximum established quota.

$$X_t \leq X_{max} \quad t \in T$$

(4.16)

Restriction on staff teams: The number of people involved in the project can not exceed a maximum established quota.

$$Y_t \leq Y_{max} \quad t \in T$$

(4.17)

No negativity restriction:

$$X_t, Y_t \geq 0 \quad T_t \geq 1 \text{ and integer}$$

(4.18)

The number of mine-deactivating technicians in period \( t = X_t/l \). The problem is solved by assigning a whole number to the number of helicopters in each period if previously known, or by fixing a large number \( G \) that guarantees feasibility (fractional restriction is eliminated this way), and the resulting linear problem is solved. The process is repeated by decreasing in each step the number of helicopters by one, starting with the first period, and the associated linear model is applied until the number of robots is minimized. The process is repeated until the number of helicopters for the last planning period is established. This procedure takes advantage of the increasing monotonic characteristic of the objective function, and optimization is guaranteed. The process is presented in Figure 1.

5 Results

The Colombian case was analyzed as a pilot test. The Colombian army has five divisions which are made up of 19
brigades. Since each brigade is responsible for a particular territory, a distribution center was located in each of them in order to supply all influence zones. It is foreseen that robots are transported and distributed by helicopter. An additional consideration of the pilot test is that robots’ life-span is the same as that established during planning.

Figure 1: Solution Algorithm

5.1 Location model results

- Plant location: the model identified division 1 as the headquarters.
• Logistics from plants to stores: The number of robots dispatched from division 1 to the 19 brigades is shown in the following table:

<table>
<thead>
<tr>
<th>Brigade</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robots</td>
<td>17</td>
<td>5</td>
<td>9</td>
<td>25</td>
<td>65</td>
<td>11</td>
<td>13</td>
<td>25</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>Brigade</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Robots</td>
<td>18</td>
<td>5</td>
<td>7</td>
<td>18</td>
<td>1</td>
<td>8</td>
<td>5</td>
<td>18</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Planning model results

• Production dynamics: 282 robots are produced during the first period

• Employment dynamics: 75 groups of two people are employed to produce robots in the first period, and 5 people for maintenance during the planning period.

• Transportation and distribution: due to the characteristics of the problem, only one helicopter is used.

6 Conclusions

This article presents a modeling process that helps to make the strategic decisions and to identify the operation and possession tactics of a domestic supply chain that will support the construction, transportation and distribution of robots for mine-clearance.

The strategic model is based on the work of Pooley (1985), and determines the chain topology. The tactic model allows the planning of a minefield eradication system, so that infrastructure costs are minimized and the necessary resources reduced to carry out the project.
The model proposed combines linear and whole variables, and includes fractional restrictions; the problem is solved through a procedure that takes into account the monotonicity of the objective function.

The separation of strategic decisions from tactic decisions results in mathematical programming that are efficiently solved in small problems by using the Branch and Bound algorithm, as well as a linear relaxation algorithm. For medium and large-sized problems, the strategic problem may be solved by Benders’ decomposition, in the way shown by Geoffrion and Graves (1974).

New research considerations suggest the inclusion of reliability in the supply, and of stochasticity in the demand.

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