Supply Chain Optimization of the distribution of mosquito nets in Ivory Coast

Irineu de Brito Junior  
*Department of Production Engineering, University of Sao Paulo  
Department of Logistics, FATEC Jessen Vidal S J Campos, Brazil*

Silvia Uneddu  
*Emergency & Field Logistics Manager, UNICEF Supply Division, Copenhagen, Denmark*

Paulo Gonçalves (paulo.goncalves@usi.ch)  
*University of Lugano, Switzerland*

**Abstract**

The use of insecticide-treated mosquito nets is one of the most effective ways to reduce malaria deaths. To help plan UNICEF’s distribution of 12 million bed-nets in Ivory Coast, we developed a model to optimize the costs from purchasing and prepositioning at Districts level, achieving 7% logistics cost reduction.

**Keywords:** Humanitarian Logistics, Linear programming, Procurement & Distribution, Malaria

**Introduction**

Despite major gains in life-saving interventions, malaria is still a major cause of death among children in developing countries. About 1,200 children under the age of 5 die every day of malaria and in Sub-Saharan Africa malaria accounts for 14% of all child related deaths (Unicef 2013). Malaria is caused by five different species of parasites that affect humans, all belonging to the genus Plasmodium: *P. falciparum, P. vivax, P. ovale, P. malariae and P. knowlesi*. Malaria caused by *P. falciparum* is the most deadly form, and it is present primarily in Africa (WHO, 2013). The intensification of malaria control in the last ten years has had a significant role in the rapid decline of under-five mortality rates in Africa (The Economist, 2012). For instance, of the 3.3 million deaths prevented between 2001 and 2012, about 90% are children under the age of 5 from sub-Saharan Africa. Considering overall child mortality rates in sub-Saharan Africa since 2000, this figure represents 20% of about 15 million deaths avoided. Hence, the reduction in malaria related deaths has a significant impact in achieving the United Nations Millennium Development Goal (MDG) 4: to reduce by two thirds the under 5 mortality rates between 1990 and 2015 (UN, 2005).

One of the most effective ways to prevent malaria transmission and reduce deaths among children is the regular use of long lasting insecticidal nets (LLINs). (Unicef 2014a). The World Malaria Report 2013 (WHO, 2013) indicates that every year at least 150 million LLINs are required to protect the population at risk of malaria in sub-Saharan Africa countries. Despite
significant efforts, the world has not yet been able to supply the annual required quantity of LLINs to protect the population at risk of malaria. Still, there has been impressive progress, from 2004 to 2013 the number of LLINs annually delivered to sub-Saharan Africa malaria-endemic countries went up from 6 million to 136 million. It is estimated that in 2014, 200 million of LLINs will be delivered.

When universal coverage – one net for every two people – is reached this simple, effective barrier can reduce child mortality by up to 20 per cent. Fighting malaria not only saves the lives of children, but also yields many other health and economic benefits for affected communities (UNICEF, 2014a).

In the last five years, UNICEF supported LLINs campaigns in over 30 countries in sub-Saharan Africa with the procurement and distribution of 120 million LLINs (Unicef 2014a).

In this study, we develop a transshipment network flow model to optimize the logistics costs for the mass campaign involving the procurement and distribution of LLINs in Ivory Coast (Cote d’Ivoire CIV) in 2014. In order to achieve the goal, the model considers the following: i) number and size of containers to be used for each one of the 71 Health Districts; ii) from which suppliers to purchase and which port to use at origin, a decision that is also influenced by the cost of purchasing containers in each of the ports of origin; iii) in which port in CIV the containers should be received; and iv) whether or not to use any cities in CIV as consolidation point to later on preposition at the 71 Health Districts.

The paper has been structured as follow: i) presentation of the problem, ii) background of humanitarian logistics, iii) presentation and explanation of the mathematical model, iv) case study, v) results and discussions, and vi) conclusions.

The Problem

Malaria is still endemic in CIV and constitutes one of the key public health problems. Malaria is also included as one of the priorities of the National Health Development Plan 2012-2015 (PNDS).

As the leading cause of morbidity and mortality in the country, malaria is the cause of 43% of cases seen in health facilities, constitutes 24% of hospital cases and is the cause of 26% of hospital deaths (Global Fund, 2013).

To address this situation, two main objectives have been established: i) to achieve and maintain universal coverage by the end of 2014 and that at least 80% of the population sleeps under the LLINs by 2015, ii) to raise awareness throughout the country on the importance of sleeping under the LLINs. The campaign which will take place in 2014, will allow the replacement of the LLINs previously distributed in 2011.

The project

The massive distribution will be done in 5 phases: the first two phases (called pilot phases) funded by the World Bank and implemented by CARE, and the last three phases funded by the Global Fund and implemented by UNICEF. In each of the phases, the implementing partner is responsible for the procurement and distribution of LLINs. In its pilot phase Care has distributed about 1.8 million LLINs during July-December 2013. UNICEF will distribute about 12 million LLINs between June-December 2014.
Figure 1 illustrates the Ivory Coast map, the ports and hubs, and the phases of distribution

Figure 1 – Phases of distribution in Ivory Coast

Many are the reasons which highly motivated the authors to embark in this project and the main ones can be summarized below:

- The 2014 mass campaign in CIV is part of “Plan National De Developpement Sanitaire 2012-2015”. The plan was developed by the Ministry of Health in CIV and includes the health priorities of the country as well the international commitments as indicated in the Millennium Development Goals. And malaria is reported to be the leading cause of morbidity and mortality in CIV, in children under 5 years (Cote D’Ivoire 2012).

- Malaria is a preventable disease but still today is responsible for one million deaths a year, and the majority are children under five. This means that a child dies every 30 seconds from malaria and 90 per cent of malaria cases happen in sub-Saharan African countries. There is no vaccine for malaria yet and sleeping under an insecticide-treated mosquito net is the most effective way to prevent malaria transmission. (Unicef 2014b)

- The Millennium Development Goal Report 2013 indicates that significant results in child survival have been achieved so far, but double of the efforts are required from countries and international agencies to meet the global target. In 2012 Unicef launched “A promise Renewed” initiative which aims to support partners to fulfill the renewed promise to child survival. By 2011 50 countries, out of 99 countries, were on track in reducing the rates of malaria cases by 75 per cent by 2015. This is a tremendous achievement which needs to be maintained and further improved with the ongoing distribution of LLINs. (UN, 2013)

- If today sleeping under an insecticide-treated mosquito net is the most effective way to prevent malaria transmission, we need to do the utmost to ensure that each and
every child can sleep under it. We need to work with partners and Governments to strengthen and optimize their/our supply chain to ensure we achieve the objective of universal coverage. Malaria can still be considered a disease of poverty, affecting mainly children under five from poor families and those living in rural areas: we have the moral obligation to reach also those children.

- LLINs campaigns are often complex due to the challenging environments where distributions usually take place, due to operations magnitude, limited resources and funding and due to the many variables which need to be taken into account. This is why the use of modeling can greatly support both the planning and implementation process of the campaigns.

**The mathematical model**

The goal of the transshipment model is to optimize the logistics costs in CIV for the LLINs campaign taking place in 2014. The following information is considered: to i) the number and size of containers to be used for each one of the 71 Health Districts; ii) from which suppliers to purchase and which port to use at origin, a decision that is also influenced by the cost of purchasing containers in each of the ports of origin; iii) in which port in CIV the containers should be received; and iv) whether or not to use any cities in CIV as consolidation point to later on preposition at the 71 Health Districts.

Figure 2 illustrates the structure of the model.
## Nomenclature

### Index sets

- **P**: Products of each supplier \( p \in P \)
- **C**: Type of container \( c \in C \)
- **I**: Suppliers \( i \in I \)
- **J**: Origin port \( j \in J \)
- **K**: CIV port (or hub) \( k \in K \)
- **D**: Districts \( d \in D \)

### Parameters (unit)

- \( c_{spij} \): Transportation cost of a container \( c \) with products \( p \) from supplier \( i \) to origin port \( j \) (US$/container).
- \( co_{pckj} \): Transportation cost of a container \( c \) with products \( p \) from origin port \( j \) to CIV port (or hub) \( k \), (US$/container).
- \( cp_{pckd} \): Transportation cost of a container \( c \) with products \( p \) from CIV port (or hub) \( k \) to district \( d \) (US$/container).
- \( pr_p \): Cost of product \( p \) (US$).
- \( cc_{cj} \): Cost of container \( c \) at origin port \( j \) (US$).
- \( dm_d \): Demand of LLINs at district \( d \).
- \( sc_{pi} \): Capacity of supplier \( i \) to produce LLINs.
- \( nq_{pc} \): Quantity of LLINs that a container \( c \) of product \( p \) contains.
- \( as_{pij} \): Binary parameter that indicates if a route from supplier \( i \) to origin port \( j \) is available for product \( p \).
- \( ao_{pjk} \): Binary parameter that indicates if a route from origin port \( j \) to CIV port (or hub) \( k \) is available for product \( p \).
- \( ap_{pkd} \): Binary parameter that indicates if a route from CIV port (or hub) \( k \) to district \( d \) is available for product \( p \).
- \( bigM \): Big number auxiliary, used to assure that a district is supplied by one product only.

### Decision variables

- \( TS_{pcij} \): Quantity of containers \( c \) with products \( p \) transferred from supplier \( i \) to origin port \( j \).
- \( TO_{pckj} \): Quantity of containers \( c \) with products \( p \) transferred from origin port \( j \) to CIV port (or hub) \( k \).
- \( TP_{pckd} \): Quantity of containers \( c \) with products \( p \) transferred from CIV port (or hub) \( k \) to district \( d \).
- \( Z_{pd} \): Binary auxiliary that assumes 1 if a district is supplied by a product \( p \) and 0 otherwise. Used to assure that a district is supplied by one product only.

### Mathematical Formulation

**Objective function:**

\[
\sum_{p \in P} \sum_{i \in I} \sum_{j \in J} c_{spij} TS_{pcij} + \sum_{p \in P} \sum_{j \in J} co_{pckj} TO_{pckj} + \sum_{p \in P} \sum_{k \in K} \sum_{d \in D} cp_{pckd} TP_{pckd} \rightarrow \min
\]
\[
\min TC = \sum_{p} \sum_{c} \sum_{i} \sum_{j} (cs_{pcij} \times TS_{pcij}) + \sum_{p} \sum_{c} \sum_{j} \sum_{k} (co_{pcjk} \times TO_{pcjk}) + \sum_{p} \sum_{c} \sum_{k} \sum_{d} (cp_{pkcjd} \times TP_{pkcjd}) + \sum_{p} \sum_{c} \sum_{j} \sum_{k} (nq_{pc} \times pr_{p} \times TS_{pcij}) + \sum_{p} \sum_{c} \sum_{j} \sum_{k} (cc_{cj} \times TO_{pcjk}) 
\]

(1)

Subject to:

\[
\sum_{j} TS_{pcij} = \sum_{k} TO_{pcjk} \quad \forall p, c, j
\]

(2)

\[
\sum_{j} TO_{pcjk} = \sum_{d} TP_{pkcjd} \quad \forall p, c, k
\]

(3)

\[
\sum_{p} \sum_{c} \sum_{k} \sum_{d} (TP_{pkcjd} \times nq_{pc}) \geq dm_{d} \quad \forall d
\]

(4)

\[
\sum_{c} \sum_{j} (TS_{pcij} \times nq_{pc}) \leq sc_{pi} \quad \forall p, i
\]

(5)

\[
TS_{pcij} \times as_{pij} \geq TS_{pcij} \quad \forall p, c, i, j
\]

(6)

\[
TO_{pcjk} \times ao_{pkj} \geq TO_{pcjk} \quad \forall p, c, j, k
\]

(7)

\[
TP_{pkcjd} \times ap_{pkd} \geq TP_{pkcjd} \quad \forall p, c, k, d
\]

(8)

\[
\sum_{c} \sum_{k} TP_{pkcjd} \leq Z_{pd} \times bigM \quad \forall p, d
\]

(9)

\[
\sum_{c} \sum_{k} TP_{pkcjd} \geq Z_{pd} \quad \forall p, d
\]

(10)

\[
\sum_{p} Z_{pd} = 1 \quad \forall d
\]

(11)

\[
TS_{pcij}, TO_{pcjk}, TP_{pkcjd} \in \mathbb{R}^+
\]

(12)

\[
Z_{pd} \in \{0,1\}
\]

(13)

In the objective function (1) the first term represents the transportation costs which apply from suppliers to ports of origin, the second refers to transportation costs from ports of origin to CIV ports/hubs, the third term represents the transportation costs from CIV ports/hubs to the 71 Health Districts. The forth represents the purchasing costs of the LLINs and the last term the purchasing costs of the containers. To assure products traceability until delivery to the Health Districts the index \( p \) is retained in all parts of the equation.

Constraints: (2) and (3) are flow conservation at \( j \) and \( k \) respectively, (4) assures that demand at district \( d \) is satisfied, (5) limits the quantities purchased according to the supplier \( i \).
production capacity of LLINs $p$. The next three constraints assure only the use of the available routes from supplier $i$ to port of origin $j$ (6), from port of origin $j$ to CIV port (or hub) $k$ (7), and from CIV port (or hub) $k$ to Health District $d$ (8). Constraints (9) and (10) are used to determine $Z$ which assumes 1 if a district is supplied by a product $p$ and 0 otherwise, and (11) assures that a district is supplied exclusively by one product $p$. Finally, constraints (12) and (13) define integer and binary variables, respectively.

**Case study**

The proposed optimization model is applied to the distribution of 12 million LLINs in CIV. The LLINs are purchased from various suppliers based in Asia and are delivered by the suppliers to the nearest ports in Asia: Haiphong and Ho Chi Minh (Vietnam), Chennai (India), Bangkok (Thailand), Qingdao, Shanghai and Tianjin (China).

There are two main ports in CIV (Abidjan and San Pedro) and three cities which could be used as strategic hubs for the consolidation of the containers. The cities are: Ferkessedougou, Yamoussoukro and Bouake and, in the model, they are considered as possible destinations where the Freight Forwarder could deliver the LLINs. From the ports of arrival (or from the three main hubs) the LLINs are sent down the supply chain to the 71 Health Districts, where they will be prepositioned before the distribution takes place. With the exception of the LLINs planned for the Abidjan region, the LLINs have to be delivered to the Health Districts in containers. This option is meant to address one of the main challenges encountered in the past LLINs campaigns: the lack of storage capacity at Health District level which also poses a security concern.

Another important lesson learnt from previous campaigns is the importance to ensure that each Health District receives LLINs supplied exclusively by one supplier: this is to avoid any kind of confusion when the distribution will take place. This requirement has been reflected in the model as a constraint.

**Input data**

The incoterm used is CIP: suppliers are responsible to deliver the LLINs in container up to the port of origin (in Asia). There will be no costs when suppliers are located in the same city like the port. The container size could be of 20 ft, 40 ft and 40 ft HC (high-cube). The freight costs to ship the containers from the Asian ports to the ports in CIV (as well as to the three main hubs in CIV) were obtained through market research and includes local insurance in CIV, customs clearance and duties, port storage and offloading at warehouse both at the ports and at the three hubs.

The transportation costs from the CIV ports (and from the three hubs) to the 71 Health Districts was calculated using a linear regression with a coefficient of determination $R^2 = 0.99$, which takes into consideration the distance between CIV ports/hubs and the Health Districts.

\[
\text{Inland cost} = 395.60 + 2.45 \times \text{distance} \quad (14)
\]

Suppliers can differ in terms of: i) LLINs production capacity; ii) stuffing capacity (as packaging of the nets can be different from one supplier to another); iii) price of the nets. The model takes these three factors into consideration and the quantity of LLINs that a container $c$ of product $p$ contains exactly reflects the stuffing capacity.
To meet the target of universal access, it is calculated that one LLIN is distributed every two people at risk of malaria. However, for procurement purposes, WHO recommends an overall ratio of one LLIN for every 1.8 persons in the target population (WHO 2013). In the model the demand reflects this recommendation.

Security concerns, rainy season and increase in CIV export activities can affect the transportation options. To address this potential bottleneck the model takes into consideration three binary parameters that indicate if a route is available from supplier $i$ to port of origin $j$, from port of origin $j$ to CIV ports (or hubs) $k$, and from CIV ports (or hubs) $k$ to Health Districts $d$. The big number auxiliary was set as $10^7$.

**Results and discussion**

The model was implemented using the software AIMMS 3.13, CPLEX solver 12.5, processor Intel Core 2 Quad® Q9650 CPU 3GHz, 4 Gb RAM, 32-bit operating system Windows7 ®. It took different time to solve the three phases: 13’15” (phase 3), 24’52” (phase 1), and 25’38” (phase 2). For phase 3 the model found the optimal solution in a shorter time mainly because in this phase all Health Districts are located very close to each other.

The model was implemented for all the three phases of the LLINs campaign. The result indicates, for each one of the 71 Health Districts, the following: i) from which supplier and from which port of origin to ship the LLINs ii) number and size of containers to be used to deliver the LLINs to the Health Districts, iii) which port and/or hub in CIV the LLINs should be delivered to, iv) which port (and/or hub) in CIV the 71 Health Districts should receive the LLINs from, v) total logistics and procurement costs.

Table 1 shows the number and the sizes of containers that each CIV port and/or hub will receive from each supplier and port of origin. This is indicated for all three phases.

<table>
<thead>
<tr>
<th>Supplier Origin Port</th>
<th>Supplier I Haiphong</th>
<th>Supplier III Chennai</th>
<th>Supplier IV Qingdao</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIV Port / Hub</td>
<td>40ft</td>
<td>40ft HC</td>
<td>20ft</td>
<td>40ft</td>
</tr>
<tr>
<td>Abidjan</td>
<td>Phase 1</td>
<td>1</td>
<td>23</td>
<td>40ft</td>
</tr>
<tr>
<td></td>
<td>Phase 2</td>
<td>3</td>
<td>4</td>
<td>40ft</td>
</tr>
<tr>
<td></td>
<td>Phase 3</td>
<td>121</td>
<td>7</td>
<td>40ft</td>
</tr>
<tr>
<td>San Pedro</td>
<td>Phase 1</td>
<td>1</td>
<td>2</td>
<td>40ft</td>
</tr>
<tr>
<td></td>
<td>Phase 2</td>
<td>1</td>
<td>68</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Phase 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yamoussoukro</td>
<td>Phase 1</td>
<td>14</td>
<td></td>
<td>40ft</td>
</tr>
<tr>
<td></td>
<td>Phase 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phase 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bouake</td>
<td>Phase 1</td>
<td>16</td>
<td>2</td>
<td>40ft</td>
</tr>
<tr>
<td></td>
<td>Phase 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phase 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>248</td>
<td>14</td>
<td>11</td>
</tr>
</tbody>
</table>
Out of five suppliers, the model suggests procuring from three suppliers only and to use three ports at origin that is the same as indicated in the CIP Incoterm. In most of the cases, the 40 ft HC is the size which better optimizes the space and reduces the transportation costs. With the exception of Abidjan port, neither San Pedro nor the three hubs are utilized for all the three phases; Ferkessodougou hub is not used at all.

Among the three phases, phase I has the Health Districts located quite far both from Abidjan and from San Pedro port. For this phase only, the model proposes to use as transshipment points: Abidjan port, San Pedro port, Yamoussoukro hub, as well as Bouake hub. Phase II has only one container assigned by the model to arrive in Yamoussoukro; however after evaluating this option, it was decided not to use Yamoussoukro for phase II.

Table 2 below shows how many Health Districts each port/hub in CIV will supply for each and every phase of the campaign. It is noted that Abidjan is the port overall supplying more districts, especially in phase III, being this the phase covering Abidjan region. Phase II is mainly served by San Pedro and this reflects the geographical position of the districts in relation to the port.

<table>
<thead>
<tr>
<th>Port / Hub</th>
<th>Abidjan</th>
<th>San Pedro</th>
<th>Yamoussoukro</th>
<th>Bouake</th>
<th>Total Containers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>9</td>
<td>4</td>
<td>9</td>
<td>6</td>
<td>28</td>
</tr>
<tr>
<td>Phase 2</td>
<td>4</td>
<td>20</td>
<td>1</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Phase 3</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
<td>24</td>
<td>10</td>
<td>6</td>
<td>74</td>
</tr>
</tbody>
</table>

As we can see from the results, the model suggests the use of consolidation points in CIV for three main reasons: i) to reduce the last mile transportation and therefore the overall transport costs, ii) to address a possible bottleneck represented by the specific equipment required to handle the containers at district level; iii) to allow the usage of smaller trucks to reach the remote areas.

Another relevant aspect to consider is the overall coordination of the supply chain. Having consolidation points would enhance coordination among the stakeholders and would greatly facilitate a prompt reaction in case of unforeseen situations and bottlenecks which could occur during the implementation of the campaign.

Comparison between initial situation and the model results

Based on information available at the beginning of the project, UNICEF’s first supply and distribution plan proposed to use 5 suppliers based in Asia, to ship from 4 ports of origin (depending on the location of the suppliers), to use over 500 40-feet containers, and to use Abidjan as the only port of arrival in CIV. It was soon realized the importance of exploring additional options to ensure an optimal planning for this massive campaign. Organizing the shipment and the distribution of 12 million LLINs requires a strong coordination among the stakeholders and a meticulous supply chain plan.

Comparing the results of the model with the first supply and distribution plan we had reduction of the logistics costs of 7 per cent. It should be noted that the real costs of procurement, freight, and in-land transportation have been omitted due to confidentiality.
Conclusions

This work presented a case to distribute 12 million LLINs in CIV. The results indicated the number and size of containers to be used for each one of the 71 Health Districts, which suppliers to purchase and which port to use at origin use, in which port in CIV the containers should be received, use or not hubs in CIV as consolidation point to later on preposition at the 71 Health Districts. The modelling process promoted a reduction of the logistics costs of 7 per cent.

Planning the campaign using mathematical modeling reduces the purchasing and logistics costs and increases impact for each dollar spent (value for money). The use of both ports does also provide an optimal option to limit the congestion of the main port, Abidjan and, together with the hubs; this also allows more control over the entire supply chain.

This work also highlights the importance that coordination has, especially when dealing with complex supply chain project like mass distribution of LLINs. More than the values the model shows an insight of the problem.

Acknowledgments

The authors would like to thank colleagues from the UNICEF Supply Division, from the Country Office in Ivory Coast, and from the Regional Office for their support and contribution to this project. The authors also thank the Brazilian funding agency CAPES Foundation, Ministry of Education of Brazil, for its support to one of the authors.

References


