Lecture Notes in Management Science (2014) Vol. **6**: 23–31
6th International Conference on Applied Operational Research, Proceedings

ISSN 2008-0050 (Print), ISSN 1927-0097 (Online)

Blood supply chain with insufficient supply: a case study of location and routing in Thailand

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Abstract. Decision making on facility locations for blood services and blood distribution plan has an impact on the efficiency of blood supply chain and logistics systems. In the blood supply chain operated by the Thai Red Cross Society (TRCS), problems are faced with amounts of blood collected in different provinces of Thailand being insufficient to meet demand. A proposal has been made to extend this network of blood centres using low-cost collection and distribution centres. Increasing numbers of fixed collection sites can improve access for donors. In addition, some facilities can perform preparation and storage for blood that hospitals can receive directly. Selecting sites for these two types of facility within a limited investment budget informs the strategic plan of this non-profit organisation. Furthermore, we consider the blood delivery problem to hospitals under variable and insufficient supplies of blood. Hospitals are assigned either to fixed routes or variable routes according to their location. Blood is supplied weekly to hospitals in the fixed route, while the frequencies of blood distribution to hospitals in the variable routes changes with the quantity of blood available daily. In the paper, we present a novel binary integer programming model for this location-allocation problem based on objectives of improving supply of blood products while reducing costs of transportation. Furthermore, we propose an online system for updating the delivery schedule over the planning horizon. Different policies for allocation and routing are compared, with a case study in northern Thailand. Computational results are reported, using real life data that are of practical importance to decision makers.

Keywords: blood supply chain; facility; online algorithm; distribution; developing country

Introduction

Blood is a perishable product which suffers from physical deterioration, with specific, fixed shelf life. Although its value during the shelf life is constant, fresh blood is preferred for treatment. Moreover, an amount of blood supply which is limited and dynamic depends on the number of walk-in donors. An organisation must rely on an effective supply chain network. Facilities and distribution options are important parts of supply chain systems. Therefore, it is a challenge to determine the locations of different types of blood service facilities which are the essential nature of the blood supply chain in either collecting blood from donors or delivering blood products to hospitals, Moreover, it includes determining a regular schedule for distribution of blood over the period of time to different hospitals for use in conditions of variable and insufficient blood supply of particular developing countries. Their budgets are limited for setting up service facilities and running the operations. In the paper, Thailand is used as the case study to provide an application of location, allocation and routing policies tested.

This paper presents locational analysis for these two types of facility, and the allocation of demand to either such new facilities or existing blood centres. Location-allocation modelling has a research base for a variety of applications in the healthcare arena. For example, the classical Maximal Covering Location Problem, formulated originally by Church and ReVelle (1974), has been widely employed in emergency service applications to maximise coverage of demand points within the predetermined distance or travel time. Similarly, variations on the *p-Median* Model (Hakimi 1964; Hakimi 1965) have been proposed to locate healthcare facilities according to minimised demand-weighted average travel distance, given a fixed number of *p* facilities (Smith *et al*., 2013).

Moreover, decisions of distribution for a product or service involves the Dynamic Vehicle Routing Problem (DVRP) which is a variant of vehicle routing problem related to dynamic requests of customer nodes (Wilson and Colvin, 1977; Campbell and Savelsbergh, 2005; Montemanni *et al*., 2007; Ferrucci *et al*,, 2009; Azi *et al*., 2011; and Xu *et al*., 2013). Hemmelmayr *et al*. (2009) applied a Variable Neighbourhood Search (VNS) to solve the Periodic Vehicle Routing Problem (PVRP), without a time window for blood distribution. Most published papers focus on the dynamic request or demand side. However, this paper focuses on the dynamic supply side. We also propose a number of algorithms for the online allocation and routing of blood supplies. A case study is presented in northern Thailand. The analysis includes a total of more than 110 hospitals, with 29 hospitals considered in the variable route. The study is expected to be a pilot for other regions of Thailand.

The rest of this paper is structured as follows. Section 2 will describe backgrounds. Section 3 looks at the integer linear programming (ILP) model for location-allocation problem and the solution methods by heuristics algorithms for online scheduling blood distribution. Computational experiments on the case study and comparison with the results on different policies are provided in Section 4. Concluding remarks include the benefits gained by the study and future recommendations in Section 5. Finally, the conclusion and further study are presented in the Section 6.

Problem background

The Thai Red Cross Society (TRCS) has responsibility for blood collection and delivery services throughout the seventy seven provinces of Thailand. Key to these services are the National Blood Centre (NBC) in Bangkok and twelve Regional Blood Centres

(RBCs) located in different provinces of the country, all of which offer facilities for donation of blood, screening and distribution. Both the NBC and RBCs distribute blood to hospitals in all provinces, as determined by government administration. The ultimate mission of the TRCS is ensuring sufficient safe blood supply and the same quality standards across the country. These activities are typical of blood centres in other countries. Blood screening and tests carried out include tests for blood groups and for infections such as Hepatitis, Syphilis and Human Immunodeficiency Virus (HIV). Whole blood is centrifuged into blood products in the form of red blood cells, plasma, and platelets. Safe blood is stored for subsequent distribution to hospitals.

To study blood distribution, we focus on the northern region of Thailand. There are (n = 112) hospitals which receive blood distributed from the RBC at Chiang Mai province. On each day, vehicle will leave from the RBC and visit various hospitals, and then return to the RBC. Hospitals are classified into two groups by their geographical location in order to design types of routes: 1) Fixed route 2) Variable route. The administrator has decided the conditions of classification for two different routes. A variable route consists of the hospitals closest to the RBC or a distance not over 70 kilometres (travelling time < 1 hour), while the hospitals which are far from the RBC are included in a fixed route. There are 83 hospitals in fixed routes and 29 hospitals in variable routes.

Solution Methods

Location-Allocation Problem for two different types of blood service facilities

Donors give blood either at one of the two types of blood service facilities proposed or at the NBC or RBCs. Transportation of whole blood and blood products is as follows: all blood collected at a type 1 donation centre goes straight to an allocated RBC. On the other hand, only samples of blood collected at Type 2 donation centres are sent to an RBC and results of screening and testing are reported online. After testing, safe blood products are distributed to demand points at hospitals. Locations for both types of blood service facilities are chosen according to a weighted sum of three criteria, of which the first is the estimated sum of donations at candidate sites. Secondly, total distances are summed from type 1 and 2 facilities to an allocated RBC. Thirdly, total distances from RBCs or Type 2 distribution centres to hospital demand points are summed, weighted by estimated quantity of blood products transported. Criteria weights are supplied by the decision maker. The model makes the following assumptions: that donations at all candidate facility sites can be estimated for the planned time period, that demand from hospitals can similarly be estimated, that a total budget for establishing the new facilities is known, and that the decision maker can weigh the relative importance of improving supply against improving transportation costs.

Parameters

d_{ik}	*distance between the i^{th} hospital and the k^{th} RBC site,* $i \in I,\ k \in K$
d_{jk}	*distance between the j^{th} facility site and the k^{th} RBC site,* $j \in J,\ k \in K$

d_{ij}	*distance between the j^{th} facility site and the i^{th} hospital, $i \in I, j \in J$*
s_j	*annual expected amount of blood collected at the j^{th} donation room in units of blood, $j \in J$*
u_i	*average quantity of blood usage at the i^{th} hospital in units of blood, $i \in I$*
W_1, W_2, W_3	*weight of the objective functions*

Decision variables

$$x_{1ik} = \begin{cases} 1, \text{ if the } i^{th} \text{ hospital is allocated to the } k^{th} \text{ RBC} \\ 0, \text{ otherwise} \end{cases}$$

$$x_{2ij} = \begin{cases} 1, \text{ if the } i^{th} \text{ hospital is allocated to a type 2 facility at the } j^{th} \text{ site} \\ 0, \text{ otherwise} \end{cases}$$

$$y_{1j} = \begin{cases} 1, \text{ if type 1 facility is opened at the } j^{th} \text{ site} \\ 0, \text{ otherwise} \end{cases}$$

$$y_{2j} = \begin{cases} 1, \text{ if type 2 facility is opened at the } j^{th} \text{ site} \\ 0, \text{ otherwise} \end{cases}$$

$$z_{1jk} = \begin{cases} 1, \text{ if type 1 facility at the } j^{th} \text{ site is allocated to the } k^{th} \text{ RBC} \\ 0, \text{ otherwise} \end{cases}$$

$$z_{2jk} = \begin{cases} 1, \text{ if type 2 facility at the } j^{th} \text{ site is allocated to the } k^{th} \text{ RBC} \\ 0, \text{ otherwise} \end{cases}$$

Model formulation for the Location-Allocation Problem for two different types of blood service facilities

The objective function (1) minimises the weighted sum of three components. The first component is the total travel distance from the two types of blood facilities to allocated RBCs. The second component is the demand-weighted distance from type 2 facility or RBCs to allocated demand sites. The final component is the expected sum of blood donated during the planning period.

Minimise

$$w_1\left(\sum_j\sum_k z_{1jk}d_{jk} + \sum_j\sum_k z_{2jk}\, d_{jk}\right) + w_2\left(\sum_i\sum_k x_{1ik}d_{ik}u_i + \sum_i\sum_j x_{2ij}\, d_{ij}u_i\right)$$
$$-w_3\left(\sum_j y_{1j}s_j + \sum_j y_{2j}s_j\right) \tag{1}$$

Constraints ensure that each hospital is allocated to exactly one RBC or one open distribution centre. Type 1 and Type 2 facilities cannot be opened at the same site. A maximum travel time of 4 hours is imposed on blood transported between the sites, assuming 80 kph speed of travel. A budgetary constraint is included.

Online blood distribution: Fixed routes and Variable routes

Heuristics algorithms are the solution approach used for the online system because the problem is non-deterministic polynomial–time hard (NP-hard), being derived from the VRP problem. The overall system can be divided into two phases. Phase 1 consists of constructing the initial solution for the blood distribution schedule based on historical data, and Phase 2 concerns updating the solution over the period of planning once the actual amount of blood available is known. The distribution plan is then updated and is used for the next day's calculations.

Generating the initial plan

The purpose is to construct the initial plan of allocation and routing for blood over a period of a planning horizon (6 days per week). Target blood supplies are assigned for each hospital. Daily delivery routes and blood allocation are computed given the expected availability of blood and maximum permitted travel time. The Single Clarke and Wright Saving Cost algorithm proposed by Clarke and Wright (1964) is used to select hospitals for a route and assign an amount of blood to those hospitals corresponding to their target blood supply, while not exceeding the daily expected value of blood supply. The algorithm considers inserting hospitals in a route by calculating the saving costs S_{ij} between a pair of the hospital i and j, where $S_{ij} = C_{0i} + C_{0j} - C_{ij}$ and C_{ij} is the travel distance measured in kilometres between hospital nodes i and j. Saving costs are then listed in descending order. However, the solution must not violate constraints on target blood supply and maximum travel distance and the assumptions.

Rescheduling plan for blood allocation and routing

The initial schedule for blood distribution is changed when the actual information of daily blood supply has become known. This phase involves the adaptation of the initial schedule to re-calculate routes and blood allocation to hospitals. Each day's blood distribution is used to update the database of blood supplied, in order to guide the next day's rescheduling. The five policies for blood allocation and distribution are described in Table 1, while the algorithm for policy 3 is shown in Table 2.

Table 1. Five policies for blood allocation and distribution

Policy	*Brief description*
1	It is a simple policy based on the initial plan. An amount of blood assigned to hospitals on the route is adjusted by the actual amount of blood supply available
2	New hospitals are added to the initial route when actual amount of blood is greater than its expected value
3	No delivery if an amount of blood for delivery is less than the given amount
4	Consider satisfying hospitals with high volume target supply
5	Blood is collected until it can meet the target supply of hospitals.

Notation

a_t	*Total amount of blood delivered to hospitals on day t*
d_{ij}	*Distance between a pair of node i and j*
I_t	*Blood inventory on day t*
P	*Predefined level point for blood distribution*
S_t	*Blood volume available on day t*
x_{ijt}	*Path between node i to j on day t*
y_{it}	*Amount of blood delivered to hospital i on day t in initial schedule*
z_{iT}	*Changes in amount of blood delivered to hospital i on day t*
α	*Petrol price*
γ	*Fuel consumption rate*

Objective function

Minimise

$$\alpha\gamma \sum_{t=1}^{6} \left(\sum_{i=0}^{n} \sum_{j=0}^{n} x_{ijt} d_{ij}\right)$$

Table 2. Algorithm for Policy 3

Step 1: Start from initial solution given by y_{it} and x_{ijt}; t = 1,2,…, 6

Step 2: Blood is delivered on day T if $I_{T-1} + S_T \geq P$

- If $S_T > E(S_T)$, then more blood is delivered . Thus, $\sum_{i=1}^{n} z_{iT} > 0$.
  1. Delivery to hospitals where the target blood supply has not yet been reached, $\sum_{t=1}^{T-1} y_{iT} + z_{iT} \leq q_i$.
  2. Add more hospitals until $\sum_{i=1}^{n} z_{iT} = a_T$
- If $S_T < E(S_T)$, then less blood is delivered. Thus, $\sum_{i=1}^{n} z_{iT} < 0$.
  1. Reduce blood from furthest part of route/ not priority. Firstly, consider a distance

     if a priority of the hospital < 3 then

     An amount of blood for the hospital is reduced

     Else if a priority of the hospital ≥ 3 then

     Ignore the hospital and consider a new hospital which is far from the Centre
  2. Remove node
- If $S_T = E(S_T)$, then use current plan

Step 3: Update the delivery schedule on day T

Step 4: Calculate $I_T = I_{T-1} + S_T - a_T$

Step 5: Repeat Step 2 and 4 until the end of delivery day

Computational Experiment

Data

A major data source used in this study are the annual reports for years 1999 to 2009 of the National Blood Centre, Thai Red Cross Society, while Data for blood distribution study used are collected from March 2011-July 2012. All paired shortest path of nodes can be obtained using OD Cost Matrix in ArcGIS software based on the real road network in the country provided by MOT Transport Fundamental Geographic Data Set (Transport FGDS).

Computer specification and software

The proposed model for the location-allocation problem has been solved using IBM ILOG CPLEX academic version 12.2. The ILOG OPL program is embedded in Visual Basic.Net as user interface of the application program. Moreover, the online application for blood allocation and routing has been developed in Visual Basic.NET 2010. It was run on a desktop computer with Intel Core ™ 2 Duo CPU E8500 and speed 3.16 GHz. Location positions of hospitals were pinned in Google Map and saved as a Keyhole Markup Language (kml) file. DNR Garmin software was then used to convert from a kml file to a Shape file, which is a file format supported by ArcMap version 10.0, in order to calculate distances between nodes. All data were stored in Microsoft Office Access 2010. The program was written to access data via Open Database Connectivity (ODBC).

Results and Discussion

Experiments on different values of weights show that increasing w_2 and decreasing w_3 of the objective function gives the higher objective values with opening distribution centres. Equally weighted objective components were used, after discussion with the National Blood Centre. One site in the northern region, Chiang Rai province, and one site in the southern region, Chumphon province, is recommended for Type 2 facilities, with distribution centres when budgets are higher than 90 million baht. Demand from several provinces is re-allocated to receive blood from the new distribution site. Hospitals in Chiang Rai, Nan and Phayao province are assigned to the distribution site at Chiang Rai province located in the north of the country, while the distribution site at Chumphon province in the southern supports hospitals located at Chumphon, Ranong, and Prachuap Khiri Khan Province.

Table 3. Comparison of blood distribution policies for one sample of donations

Indicator/ Measurement	*Initial Solution*	*Policy1*	*Policy2*	*Policy3*	*Policy4*	*Policy5*
Total distance (km)	926.23	921.83	936.72	662.71	922.94	648.49
Total amount of allocated blood (bags)	317	342	338	330	340	342
Total Transportation Cost = $\frac{\textit{Total distance} \times \textit{Petrol prices(Baht/litre)}}{\textit{Fuel consumption rate(km/Litre)}}$	3704.92	3687.32	3746.88	2650.64	3691.76	2593.96
Average Transportation Cost per Bags (Baht/bag)	11.69	10.78	11.09	8.03	10.86	7.59
Holding Cost = *No. of bag × Cost per unit(Baht/unit/day)*	0	250	40	880	60	950
Total costs (transportation cost + inventory cost)	3704.92	3937.32	3786.88	3530.64	3702.62	3543.96
Average Processing Time(seconds)		0.05	2.13	0.46	1.37	1.04

Runs were made for budgets from 10 to 200 million baht with contrastingly the decreasing costs of transporting blood to hospitals with increasing quantities of blood collected from donors. For lower budgets, up to 70 million Baht, only the less costly Type 1 facilities are located, with rooms for donations only. At higher budgets, the more costly Type 2 facilities can also be afforded, with rooms for both donations and distribution. There is a steady decline in the logistics and transportation costs with the opening of a new distribution site.

From Table 3, both policies 3 and 5 are recommended. However, the policy 3 gives the lowest total costs and is suitable for balancing between shortage conditions and saving logistics costs. Blood should be delivered to a hospital when the total blood available is greater than the predefined level point.

Conclusions and Future Works

Blood is a much needed perishable product which is provided to hospitals for treatment. Shortage of supply of safe blood products is a severe problem in many developing countries such as Thailand. Binary Integer programming is proposed for this location-allocation problem based on contrasting objectives of improving supply while reducing transportation costs. Moreover, the quantity of blood supplied every day is dependent on blood donations of donors. Therefore, the schedule plan and routes for blood distribution over the planning horizon are changed when the blood available is known. We have addressed a planning problem which is the integration of vehicle routing problem and allocation problem for blood. It is applied to the real- life case study in the northern region. In future, uncertainty of blood request for the hospitals will be included into the problem. The algorithm can be applied to the other blood products such as platelets, and also to other perishable products and agricultural products.

Acknowledgments— The author thanks Miss Tasanee Sakuldamrongpanich who is the deputy at The National Blood Centre, Thai Red Cross Society for providing problem information and real-life data, and also thanks Assistant Professor Somchai Pathomsiri, the Header of the Civil and Environment Engineering department, Mahidol University, Thailand, for supporting knowledge about transportation systems in the country. This research has been funded by the Royal Thai Government.

References

Azi N, Gendreau M, Potvin J (2011). A dynamic vehicle routing problem with multiple delivery routes. Annals of Operations Research 199(1): 103-112.

Campbell A, Savelsbergh M (2005). Decision support for consumer direct grocery initiatives. Transportation Science 39(3): 313-327.

Church RL, ReVelle C (1974). The maximal covering location problem. Papers of the Regional Science Association, 32,101-18.

Clarke C, Wright JQ (1964). Scheduling of vehicle from a central depot to a number of delivery points. Operations Research, 12, 568–581.

Ferrucci F, Block S, Gendreau M (2009). Real-time distribution of perishable goods using past request information to anticipate future requests. In EURO Conference 2009. Bonn.
Hakimi SL (1964). Optimum locations of switching centers and the absolute centers and medians of a graph. Operations Research, 12: 450-9.
Hakimi SL (1965). Optimum distribution of switching centers in a communication network and some related graph theoretic problems.Operations Research 13: 462-75
Hemmelmayr VC, Doerner KF, Hartl RF (2009). A variable neighborhood search heuristic for periodic routing problems. European Journal of Operational Research, 195(3), 791-802.
Montemanni R, Gambardella L, Rizzoli A, Donati A (2007). Ant Colony System for a Dynamic Vehicle Routing Problem. Journal of Combinatorial Optimization 10(4): 327-343.
Smith HK, Harper PR, Potts CN (2013). Bicriteria efficiency/equity hierarchical location models for public service application. Journal of the Operational Research Society 64: 500-512.
Wilson N, Colvin N (1977). Computer control of the Rochester dial-a-ride system. Technical Report of Massachusetts Institute of Technology, Department of Civil Engineering. Massachusetts: Cambridge.
Xu Y, Wang L, Yang Y (2013). Dynamic Vehicle Routing Using an Improved Variable Neighborhood Search Algorithm. Journal of Applied Mathematics 2013: 1-12.