VEHICLE ROUTING FOR BLOOD PRODUCT DELIVERY

การจัดเส้นทางขนส่งผลิตภัณฑ์เลือด

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Abstract

This study examines a real life case from a third-party logistics service provider using vehicles to substitute for hospital ambulances. The vehicle routes of blood product delivery are designed with the primary goal to minimize travel time from the National Blood Center (NBC) to hospitals. Each vehicle starts from the NBC and performs a tour on a designed route. Hospitals in the service system are located in the Bangkok metropolitan area, and also in other provinces having an airport nearby. For the latter group, the delivery is dropped off at Don Mueang International Airport and shipped to a destination airport. Integer programming is employed and coded in IBM ILOG CPLEX. Units of blood products are relatively small, compared to the capacity of vehicles. Thus, a change in hospital demand does not affect a route. Sensitivity analysis is studied only on the length of stay. A solution methodology is tested on real data obtained from past activities. The result recommends a maximum time for length of stay at a hospital in order to obtain an optimal solution. A time reduction from the maximum length of stay does not affect the delivery pattern.

Keywords: Vehicle routing problem, Transportation and handling, Blood and blood products

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บทคัดย่อ

บทความนี้นำเสนอการออกแบบเส้นทางจัดส่งเลือดและผลิตภัณฑ์เลือด โดยมีวัตถุประสงค์หลักเพื่อใช้เวลาในการจัดส่งให้น้อยที่สุด การจัดส่งจากศูนย์บริการโลหิตแห่งชาติไปยังโรงพยาบาลต่างๆ ให้บริการโดยบริษัทขนส่ง 3PL เอกชนที่นำพาหนะมาทดแทนรถฉุกเฉินของโรงพยาบาล โรงพยาบาลที่เป็นลูกค้าอยู่ในกรุงเทพและปริมณฑล หรือเป็นโรงพยาบาลในต่างจังหวัดที่อยู่ใกล้สนามบิน ซึ่งเลือดและผลิตภัณฑ์เลือดสำหรับโรงพยาบาลในกลุ่มสุดท้ายนี้จะนำส่งที่สนามบินนานาชาติดอนเมืองไปยังสนามบินปลายทาง การศึกษานี้ใช้แบบจำลอง integer programming และโปรแกรม IBM ILOG CPLEX เพื่อหาคำตอบเส้นทางนำส่ง ขนาดบรรจุของผลิตภัณฑ์เลือดมีขนาดเล็กมากเมื่อเทียบกับขนาดของรถที่ใช้เพื่อการขนส่ง ทำให้เมื่อมีการเปลี่ยนแปลงความต้องการเลือดจะไม่ส่งผลกระทบต่อเส้นทางจัดส่งที่ออกแบบไว้ ดังนั้นการวิเคราะห์ความอ่อนไหว (sensitivity analysis) จึงไม่รวมการเปลี่ยนแปลงความต้องการผลิตภัณฑ์เลือดและศึกษาเฉพาะผลกระทบของเวลาที่รถขนส่งจอดเพื่อให้บริการ ณ โรงพยาบาล (length of stay) แบบจำลองนี้ได้ทดสอบกับข้อมูลจริงจากบริษัท 3PL ที่ให้บริการอยู่ในปัจจุบัน ผลการศึกษาแนะนำค่าระยะเวลา length of stay ในการให้บริการและการลดเวลานี้ไม่มีผลกระทบต่อเส้นทางการจัดส่ง

คำสำคัญ: ปัญหาการจัดเส้นทางการขนส่ง การขนส่งและการจัดการ เลือดและผลิตภัณฑ์เลือด

Introduction

Blood not only saves the lives of accident victims, but also is needed for patients being treated for: cancer, orthopedic surgeries, organ and marrow transplants, cardiovascular surgeries, or inherited blood disorders. Blood cannot be manufactured outside a human body. It is usually drawn as whole blood. One unit of whole blood can be divided into four different blood products/components: red blood cells (RBCs), white blood cells, platelets, and plasma. Different blood products are used differently. The Health Sciences Authority of the Singapore Government (2016) presents the usage of blood products as follows. Whole blood is used when patients have rapid and massive blood loss, like in accidents or during surgery. RBCs are used in the treatment of anemia or replacing loss of RBCs in accidents or during surgery or childbirth. Platelets are needed in treatments for dengue, leukemia, and cancer patients. Fresh frozen plasma replaces clotting factors which may be depleted in bleeding or infection. Lastly, even though white blood cells are useful, they are not usually used for transfusions as they become unfit to use after 24 hours.

The general process of a blood product supply chain is illustrated in Figure 1. It starts from blood collection from volunteer donors at a blood center or a mobile unit. Blood then goes through a rigorous screening process to reduce the risk of transmission of infectious diseases, including HIV and viral hepatitis. After complying with rules and regulations, units from donors are tested and stored or extracted before storage at a blood center. Hospitals place an order to a blood center according to a schedule of medical operations. Prior to a blood transfusion, a crossmatch test is performed to make sure that a patient's blood is compatible with a donor's blood. Our study focuses on the daily distribution between a national blood center and hospitals, to transport blood products for prescheduled operations. In Thailand, hospitals usually use an ambulance to pick up blood products at the National Blood Center (NBC) of the Thai Red Cross. However, an ambulance is a vehicle specially equipped for taking sick or injured people to and from a hospital, especially in emergencies. Therefore, an ambulance should be utilized for such a purpose. This gives an opportunity to 3PL service providers to use vehicles to substitute for ambulances in a distribution system so that ambulances will be better utilized in emergencies. Distribution of blood products is illustrated in Figure 2.

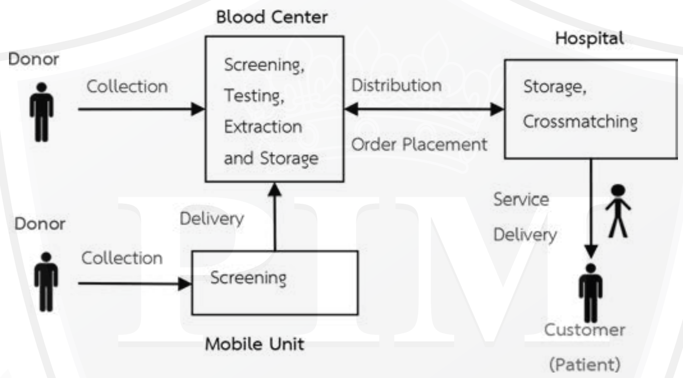

Figure 1 Supply chain of blood products (adapted from Gunpinar & Centeno, 2015)

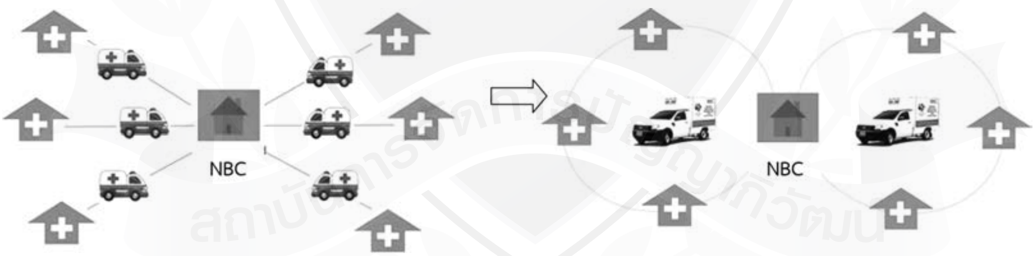

Figure 2 3PL-service vehicles substituting for ambulances in blood distribution

Our case study is a real case from the 3PL company. A hospital places an order to the system. The order's information consists of blood product type, units of blood product, and a pickup date at the NBC. The 3PL company then collects the orders, sorts by the pickup date, and designs routes to a number of hospitals (customers) with a fleet of vehicles. The optimal tour used by the group of vehicles needs to be determined. This vehicle routing problem (VRP) is formulated using integer programming with the primary objective to minimize the travel time from the NBC to hospitals. A solution determines the number of vehicles, route, sequence of delivery, and the length of stay at each stop. While most of the past literature in blood transportation seeks the routing for a mobile blood donation system to collect blood from donation sites, our study presents routes to transport blood products to hospitals, used by a 3PL service provider.

Problem definition and related literature

Problem definition

This is a real case study from a transportation service company in the healthcare industry. Hospitals can place orders 24 hours a day in the 3PL-company system. The orders are collected for the first round at 5 A.M. If there is an order, a vehicle is sent to a queue at the NBC. Orders are collected again at 8.15 A.M. Routes are then designed for delivery. Blood products released from the NBC are packed in a temperature-controlled transport container for the designed route and leave the NBC at 9 A.M. A vehicle must deliver blood products to hospitals no later than 2 P.M. Thus, the total working time on each route is five hours. Although, there is no strict delivery time window at each hospital, a single deterministic 5-hour time constraint is used. When the last order on a route is delivered, a vehicle is not required to come back to the NBC. Therefore, the total time is when a vehicle leaves the NBC at 9 A.M. until the last delivery arrives at the last hospital. The total time on a route consists of two metrics: 1) accumulated travel time from one location to another location until the last delivery reaches the hospital, and 2) the length of stay accumulated from each hospital, except at the last hospital because the accumulated time is cut off when the last delivery arrives at the last hospital. The hospitals using the service are mostly located in the Bangkok metropolitan area. These orders are delivered by vehicles. Some hospitals in the system are located far from Bangkok, such as in Phisanulok. In this case, the blood products are dropped off by a vehicle at a selected airline at Don Mueang International Airport. This delivery is set as the first stop on a route after a vehicle leaves the NBC, in order to manage the operating time, to ensure that blood products reach the destination in good quality and fit for use. Two vehicles are assigned to the system. Notice from Figures 3 and 4 that units of blood products are relatively small compared to the capacity of vehicles. Some countries like the UK use motorcycles to deliver blood products, displayed in Figure 5.

In our study, the NBC is the only depot in the distribution system. For a single depot VRP, all vehicles must start from the origin or depot and end at the same location, with a distance dependent objective function (Braekers, Ramaekers & Nieuwenhuyse, 2016). Our study is different from the traditional VRP in three aspects. First, all vehicles start from the NBC (depot), but cannot come back to the NBC. They come back to a company. The company is located near the NBC. Hence, we use the NBC as the origin and a destination. Second, the total operating time accumulates when a vehicle departs the NBC until the last order arrives at the last hospital on the route. Therefore, the length of stay at the last hospital, and the travel time from the last hospital coming back to the NBC, are excluded in the total time. Third, the road and traffic conditions in Bangkok are a big issue. Hence, decision making is more sensitive to time than distance, and the model objective uses time dependence, not distance dependence.

Figure 3 Vehicle assigned to transport blood products. Image from Transpeed Co., Ltd

Figure 4 Blood products released from NBC, packed in a temperature-controlled transport container. Image from Transpeed Co., Ltd

Figure 5 Blood runner or blood bike emergency vehicle in UK (The Rider's Digest, 2013)

Related literature

Transportation of blood products is unique as blood is fragile and should be handled with care. Knowledge about blood handling and transportation helps to maintain the quality of blood. Concepts of blood anticoagulation and preservation, as well as storage and transportation can be found in Hardwick (2008a) and Hardwick (2008b).

Beliën & Forcé (2012) presented trends in supply chain management of blood products, including routing decisions for a delivery pattern. However, most of the past related literature applies vehicle routing for blood collection, and a mobile blood donation system (Rabbani, Aghabegloo & Farrokhi-Asl, 2016; Şahinazan, Kara & Taner, 2015; Ozener & Ekici, 2011; Yi & Scheller-Wolf, 2003). Şahinazan, Kara & Taner (2015) and Ozener & Ekici (2011) studied the maximum blood collection problem – a vehicle collects blood from mobile sites on an optimal route and comes back to the depot. Similarly, Rabbani, Aghabegloo & Farrokhi-Asl (2016) also adopted vehicle routing in finding the optimal blood mobile location while minimizing the cost, as well as maintaining the level or potential of blood collection. Yi & Scheller-Wolf (2003) presented vehicle routing with time windows and a time-dependent reward to enhance the bring-back-operation of the American Red Cross.

Sukaboon & Pathomsiri (2011), Bodhipundit & Pathomsiri (2011), and Pathomsiri & Sukaboon (2013) studied blood distribution in Thailand. Sukaboon & Pathomsiri (2011) used the Saving Algorithm to determine routes of blood distribution in the Bangkok metropolitan region, assuming that vehicles are operated by the NBC. Bodhipundit & Pathomsiri (2011) surveyed modes of blood distribution in Thailand and the associated costs. Pathomsiri & Sukaboon (2013) extended Sukaboon & Pathomsiri (2011) and used a cost effective approach to determine a fair price of delivery. Our work is similar to Sukaboon & Pathomsiri (2011) and Pathomsiri & Sukaboon (2013), but without cost analysis. Our model uses integer programming to determine the exact solution, to design the delivery routes.

There are several types of VRP mathematical models. Braekers, Ramaekers & Nieuwenhuyse (2016), De Jaegere, Defraeye & Van Nieuwenhuyse (2015), and Eksioglu, Vural & Reisman (2009) offered a state of the art and intensive review on VRP. Examples of capacitated VRP without time windows can be seen in Chandran & Raghavan (2008), Caric & Gold (2008), and Kumar & Panneerselvam (2012).

Model development

The number of hospitals can be expressed as $N = \{1, 2,.., n\}$. The vehicles travel from hospital i to hospital j with different time t_{ij} where $i,j \in n$ and $i \neq j$. Let q_i be the quantity of blood product required by hospital i where $i \in N$, and $i = 1$ means that hospital i is the origin (i.e. the NBC), and its demand is always zero. If $t_{ij} = t_{ji}$, this is called symmetrical VRP. If $t_{ij} \neq t_{ji}$, this is called unsymmetrical VRP. Our case study is unsymmetrical VRP. Time from hospital i to hospital j is not equal to the time from hospital *j* to hospital *i* because of road patterns (such as one-way, two-way) and traffic conditions. Travel time from hospital *i* to hospital *j* is different than from hospital *j* to hospital *i*. Therefore, $t_{ij} \neq t_{ji}$.

A vehicle starts from the origin or *i* = 1, and travels for a delivery to hospital *j*. Suppose we have *v* vehicles, which *K* = {1, 2,..., *v*} and the k^{th} vehicle has its own visited nodes and capacity. Let the capacity of vehicle *k* be a_k.

Indices:

i, j Hospital *i* or *j* and *i, j* ∊ *n*, N = {1, ..., n}

k Vehicle *k*, *k* ∊ *K*, K = {1, ..., v}

Parameters:

n Number of nodes

q_i Demand of blood products required by hospital *i*

a_k Capacity of vehicle *k*

r Maximum route time (*r* = 300 minutes)

t_{ij} Travel time from customer *i* to customer *j*

f_i Length of stay at hospital *i*

U_{ik} Variable used to avoid subtours, which can be interpreted as the accumulation of demand of vehicle k at node *i*

Decision variables:

X_{ijk} = 1 if vehicle *k* travels from node *i* to node *j*, 0 otherwise

Y_{ik} = 1 if vehicle *k* serves hospital *i*, 0 otherwise

The minimum-time VRP model is described below.

Minimize $\sum_{i=1}^{N}\sum_{j=2}^{N}\sum_{k=1}^{K}(t_{ij}+f_i)X_{ijk}$ (1)

Subject to

$$\sum_{j=2}^{N} X_{1jk} = 1 \qquad k \in K \qquad (2)$$

$$\sum_{j=2}^{N} X_{j1k} = 1 \qquad k \in K \qquad (3)$$

$$\sum_{k=1}^{K} X_{14k} = 1 \qquad (4)$$

$$\sum_{i=1}^{N} X_{ipk} - \sum_{j=1}^{N} X_{pjk} = 0 \qquad p \in N, k \in K \qquad (5)$$

$$\sum_{k=1}^{N} Y_{ik} = 1 \qquad i = 2 \ldots n \qquad (6)$$

$$\sum_{i=1}^{N} q_i Y_{ik} \leq a_k \qquad k \in K \qquad (7)$$

$$Y_{ik} \leq \sum_{j=1}^{N} X_{ijk} \qquad i \in N, k \in K \qquad (8)$$

$$\sum_{k=1}^{K}\sum_{i=1}^{N} X_{ijk} = 1 \qquad j = 2 \ldots n, i \neq j \qquad (9)$$

$$\sum_{i=1}^{N}\sum_{j=2, j\neq i}^{N} X_{ijk}(t_{ij}+f_i) \leq r \qquad k \in K \qquad (10)$$

$$U_{ik} \geq U_{jk} + q_i - a_k + \left(a_k * (X_{ijk} + X_{jik})\right) - \left(X_{ijk} * (q_i + q_j)\right)$$
$$k \in K, i \in N, j = 2 \ldots n, i \neq j \qquad (11)$$

$$U_{ik} \geq a_k - \left(X_{1ik} * (a_k - q_i)\right) \qquad k \in K, i \in N \qquad (12)$$

$$U_{ik} \geq q_i + \sum_{j=2}^{N} q_j * X_{jik} \qquad k \in K, i \in N \qquad (13)$$

$$X_{ijk} \epsilon \{0,1\}, \; Y_{ik} \epsilon \{0,1\} \quad i, j \,\epsilon N; k \epsilon K \qquad (14)$$

Objective function (1) is intended to minimize the total time from hospital *i* to hospital *j* by vehicle *k*. As mentioned before, the total time is the accumulated travel time plus the accumulated length of stay. The travel time from the last hospital to the NBC and the length of stay at the last hospital are excluded from the total time. This means that the time from any hospital *i* to the NBC (*j* = 1) or t_{ij} is not included so *j* = 1 is excluded, and *j* is from 2 to *n*. Constraint (2) is the guarantee that the vehicles begin at the origin. Constraint (3) makes the routes end at the origin, assuming that the NBC and company locations are the same. Recall that vehicles come back to the company, but the company is located close to the NBC. Constraint (4) guarantees that one of the vehicles travels from the NBC to Node 4 (Don Mueang International Airport). This is to send blood products by plane to hospitals located in other provinces having an airport nearby. Constraint (5) guarantees that once a vehicle services a node, it will leave that node and proceed to another destination. Constraint (6) is the condition that a node will be serviced exactly one time. Constraint (7) ensures that the total demand from every node in the route will not exceed the vehicle capacity. Constraint (8) is the condition that when vehicle k is traveling to node *i*, this is only possible when vehicle *k* travels to node *i* from the path of one particular j. Constraint (9) ensures that the vehicles travel from nodes *i* to *j*, and node *i* is not equal to node *j*. That is, *i* and *j* must be different hospitals. Constraint (10) guarantees that the total route time of each vehicle will not exceed 300 minutes (or five hours). As mentioned before, the length of stay of the last hospital and the travel time from the last hospital are excluded; therefore, *j* = 2, 3,..., *n*. Constraints (11)-(13) prevent the occurrence of a subtour. Finally, constraint (14) defines the binary decision variables.

Data

The current service has 10 hospitals in the system. Table 1 shows the numbers and names of all nodes. The first node is the NBC, which is the origin. All locations are also geographically illustrated on the map in Figure 6. Travel times between locations are collected using Google Maps. A travel time is collected every 30 minutes from 9 A.M. to 2 P.M. for five working days. After that, the data is gathered and calculated to find the average time from one node to another. A coefficient of variation (CV) of those times is calculated. Since the CVs are low, the average time represents the travel time between locations, as shown in Table 2.

Table 1 List of locations

Index	Name
1	NBC, Thai Red Cross (the origin)
2	Hospital 1
3	Hospital 2
4	Don Mueang International Airport, drop off location for Hospital 3, located in another province, having an airport nearby
5	Hospital 4
6	Hospital 5
7	Hospital 6
8	Hospital 7
9	Hospital 8
10	Hospital 9
11	Hospital 10

Figure 6 Locations on Google Maps

Table 2 Travel time between locations (minutes)

i/j	1	2	3	4	5	6	7	8	9	10	11
1	0	49.34	50.56	63.08	58.04	47.52	49.96	32.96	40.10	43.78	22.06
2	62.90	0	3.62	60.14	98.78	89.14	91.10	77.04	53.68	65.22	62.58
3	55.28	1.96	0	46.68	91.14	82.22	85.34	68.48	55.76	58.84	56.46
4	39.94	41.52	41.14	0	64.04	60.58	69.22	51.44	19.64	36.46	43.38
5	69.96	98.32	96.16	122.72	0	23.48	39.16	52.70	70.34	57.82	43.58
6	53.38	65.20	66.61	109.00	17.12	0	33.80	30.30	49.83	48.10	41.44
7	57.48	89.30	91.20	71.40	30.36	32.12	0	32.18	83.56	70.94	42.10
8	52.28	88.40	87.98	45.18	50.10	35.34	37.14	0	74.18	59.54	31.00
9	49.34	54.92	53.60	13.80	68.68	63.12	77.48	60.76	0	28.36	54.38
10	56.34	62.24	63.96	33.20	61.50	55.76	76.62	55.32	34.24	0	56.40
11	30.20	58.64	59.88	43.38	51.30	37.74	38.50	20.12	52.20	41.10	0

Numerical result and sensitivity analysis

This section presents the optimal results of the base case and the sensitivity analysis.

30 minutes for length of stay at each hospital with two vehicles

From the company report, the average time for the length of stay at a hospital is 30 minutes. The result from the mathematical model supports this information. When the length of stay exceeds 30 minutes, there is no optimal solution. The 30-minute length of stay yields two routes. Table 3 and Figure 7 show the optimal result. A vehicle on Route 1 starts from the NBC. Then, it travels to the airport and Hospitals 8, 9, 1, and 2. The other vehicle on Route 2 starts from the NBC. Then, it travels to Hospitals 10, 7, 6, 5, and 4.

The total route time is the summation of the total travel time and the total length of stay. The operating time from 9 A.M. to 2 P.M. is 300 minutes. When a vehicle arrives at the last hospital, the delivery arrives, and the accumulated total time is stopped. Therefore, the travel time from the last hospital coming back to the NBC, and the length of stay at the last hospital, are not included in the total time. The result shows that the travel times on Route 1 and Route 2 are 176.94 and 128.56 minutes, respectively. The total length of stay is accumulated from the first four hospitals (the length of stay at the last hospital is excluded.). Thus, the total length of stay is *4*(length of stay)*, which is 4*30 or 120 minutes. Hence, the total time for Routes 1 and 2 are 296.94 and 248.56, respectively.

Notice that the remaining allowed times on Routes 1 and 2 are 3.06 and 51.44 minutes, respectively. This means that a vehicle on Route 1 almost reaches the length of stay constraint, thus, a 30-minute length of stay is strictly employed at each stop.

Table 3 Optimal result

Route	Total travel time (min)	Total length of stay (min)	Total route time (min)
Route 1: 1, 4, 9, 10, 2, 3	176.94	120 (or 4*30)	296.94
Route 2: 1, 11, 8, 7, 6, 5	128.56	120 (or 4*30)	248.56

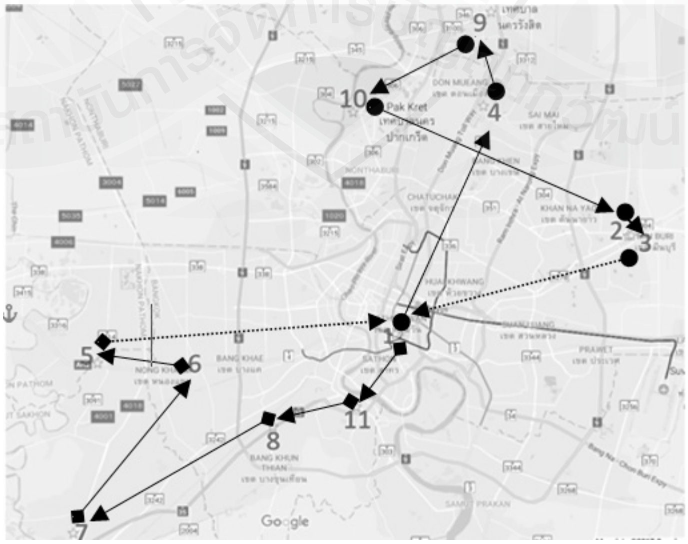

Figure 7 Optimal routes for two vehicles with 30-minute length of stay

30 minutes or less for length of stay at hospital with two vehicles

Further calculation is carried out using a length of stay of less than 30 minutes. The result shows that the accumulated travel times for Routes 1 and 2 are equal to the times in the base case, and the sequence of delivery is unchanged. This means that the time reduction for the length of stay does not affect the delivery pattern.

30 minutes or less for length of stay at hospital with two vehicles and various hospital demands

We found that changes in the hospital demand do not affect the pattern of the optimal routes. This is because units of blood products are relatively small. This makes accumulative demand relatively small, compared to vehicle capacity. Thus, the demand in this case study does not affect the delivery pattern.

Table 4 Optimal result

Length of stay at each hospital	Total travel time on R1 and R2 from NBC to the last hospital (min)	Total length of stay = 4 stops*length of stay (min)	Total route time (min)
30 min (The base case)	R1: 176.94	120	296.94
	R2: 128.56	120	248.56
29 min	R1: 176.94	116	292.94
	R2: 128.56	116	244.56
28 min	R1: 176.94	112	288.94
	R2: 128.56	112	240.56
27 min	R1: 176.94	108	284.94
	R2: 128.56	108	236.56
26 min	R1: 176.94	104	280.94
	R2: 128.56	104	232.56
25 min	R1: 176.94	100	276.94
	R2: 128.56	100	228.56
24 min	R1: 176.94	96	272.94
	R2: 128.56	96	224.56
23 min	R1: 176.94	92	268.94
	R2: 128.56	92	220.56
21 min	R1: 176.94	84	260.94
	R2: 128.56	84	212.56
20 min	R1: 176.94	80	256.94
	R2: 128.56	80	208.56

Conclusion

This paper solves a Vehicle Routing Problem (VRP) to cope with transportation for blood product delivery from the NBC to hospitals. Two vehicles of a 3PL service provider are assigned to substitute for ambulances sent from hospitals. The service provider currently uses two vehicles to serve 10 hospitals. Integer programming is employed to find an exact solution for this real case study.

The computation yields optimal results of minimum total time and a sequence of deliveries. The result suggests as follows. First, to obtain an optimal result, the length of stay should not exceed 30 minutes. Second, if the length of stay is more than 30 minutes, an additional vehicle should be added to the system in order to design optimal routes. However, vehicles will have more idle time and not be effectively utilized. Third, a reduction of the length of stay from 30 minutes does not affect the delivery pattern. When using two vehicles, Route 1's total time almost reaches five hours (the maximum time allowed on the route). Therefore, the policy of the 30-minute length of stay should be enforced rigorously. Lastly, an increasing demand for blood products also does not affect the delivery pattern. This is because the size of blood products is significantly smaller than the capacity of vehicles. For further study, more hospitals can be added to the system and the type of vehicle can be changed from a truck to a motorcycle to compare costs and service quality.

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