### DESIGNING THE BLOOD SUPPLY CHAIN: HOW MUCH, HOW AND WHERE?

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**Abstract**

**BACKGROUND:** The blood supply chain network can take many forms in different settings, depending on local factors such as geography, politics, costs, etc.; however, many developed countries are moving towards centralized facilities.  The goal for all blood distribution networks, regardless of design, remains the same: to satisfy demand at minimal cost and minimal wastage.

**STUDY DESIGN AND METHODS:** Mathematically, the blood supply system design can be viewed as a location-allocation problem, where the aim is to find the optimal location of facilities and to assign hospitals to them to minimize total system cost.  However, most location-allocation models in the blood supply chain modeling literature omit important aspects of the problem, such as selecting amongst differing methods of collection and production. In this paper, we present a location-allocation model that takes these factors into account to support strategic decision-making at different levels of centralization.

**RESULTS:** Our approach is illustrated by a case study (Colombia) to redesign the national blood supply chain under a range of realistic travel time limitations. For each scenario, an optimal supply chain configuration is obtained, together with optimal collection and production strategies. We show that the total costs for the most centralized scenario are around 40% of the costs for the least centralized scenario.

**CONCLUSION:** Centralized systems are more efficient than decentralized systems.  However, the latter may be preferred for political or geographical reasons. Our model allows decision-makers to redesign the supply network per local circumstances, and determine optimal collection and production strategies that minimize total costs.

# INTRODUCTION

The blood supply chain (BSC) can be subdivided into stages: collection, production, inventory and distribution. Blood collection is an activity that requires enormous effort: donations are voluntary, and the willingness of donors depends on factors such as distance they must travel, and level of physical discomfort, amongst others. Furthermore, different methods can be used for collection that have an impact on the number and type of finished products obtained, and their costs. Most developed countries have, or are moving towards, centralized supply chains that rely on large regional production and distribution centers; the level of centralization is, however, lower in developing countries.

Most blood products are obtained from whole blood. Each donor provides one unit of blood that is separated into different components (red blood cells (RBC), plasma, platelets and cryoprecipitate using a second separation), yielding different quantities, depending on the collection and separation strategy employed. By contrast, during apheresis collection, the donor is attached to a machine that extracts only the desired component. The equipment required for apheresis collection is considerably more expensive than that for whole-blood donation. However, the yield per donor is much greater: for example, apheresis provides five to ten times as many platelets per donation. Most studies in the modeling literature, however, only consider whole blood donation.

The benefits of centralization are well documented in the general logistics literature in terms of reduced inventory and increased economies of scale. In the BSC, production decisions must take into consideration demand for products, donations, product compatibility, and collection and production alternatives. Table 1 presents the most common collection processes.

Table 1 here

Given the vast range of collection and separation alternatives, determining an optimal network configuration is a highly challenging problem that includes production factors, collection strategies and economic, political, geographical and even cultural considerations. In this paper, we present a generic mathematical model that optimizes the design of the BSC, including decisions on collection and production strategies as well as network layout. To illustrate the approach, a case study is presented using data derived from Colombia.

## Literature review

Location decisions are typically regarded as strategic in any supply chain. [Or and Pierskalla](#_ENREF_6) 1 present an integrated mathematical model to locate blood centers and allocate hospitals to them. [Sahin et al.](#_ENREF_8) 2 present models to support decisions regarding location and allocation in Turkey. Other articles concerned with locating facilities are presented by [Cerveny 9](#_ENREF_9), [Price and Turcotte 10](#_ENREF_10) and more recently [Çetin and Sarul](#_ENREF_11) 3. [Chaiwuttisak, et al.](#_ENREF_12) 4 studied the location of low-cost blood donation and blood distribution rooms for the Thai Red Cross Society.

The production stage of the blood supply chain has received comparatively little attention in the modeling literature. [Deuermeyer and Pierskalla](#_ENREF_13) 5 and [Deuermeyer](#_ENREF_14) 6 develop an analytical model to minimize the total production costs of RBCs and platelets. [Katz, et al.](#_ENREF_16) 7 define a platelet production function, based on historical demand and deviations. [Ledman and Groh](#_ENREF_17) 8 develop production planning rules that consider demand variability and a variety of collection schemes. Special attention has been paid to platelets because of their short shelf-life; [Haijema, et al.](#_ENREF_18) 9, [Haijema, et al.](#_ENREF_19) 10 and [van Dijk, et al.](#_ENREF_20) 11 develop several models to determine optimal platelet inventories.

Design of the blood supply chain has gained relevance in recent years, with several publications focusing on building better blood networks under different circumstances such as disasters12, uncertainty13 and social aspects14. The main approach used is optimization; however, simulation has also been used to support network design decisions15. Other recent publications are aimed at studying production planning16 as well as the trade-off between whole blood and apheresis donations17. In addition, several papers regarding strategic aspects of blood supply chain management have been recently published in the blood services literature. Examples include the consequences of a centralization process using a real case in sub-Saharan Africa18, good inventory practices19 and ordering and allocation policies20.

The model in this paper is unique; it includes multiple collection and separation methods and considers four major blood products (RBCs, plasma, platelets, and cryoprecipitate), while setting location decisions simultaneously with capacity decisions.

1. **CENTRALIZATION AND DECENTRALIZATION ISSUES**

A key consideration for blood supply networks is the level of centralization. Centralization exploits economies of scale, while decentralized systems are responsive to geographical or political conditions. Examples of a decentralized system (Colombia) and a centralized system (the UK) are given in Figure 1, with locations of blood production centersshown in yellow.

Figure 1 here

In addition, staffing can be a factor that affects centralization or decentralization decisions. On the one hand, centralization may require an increase in specialized labor to handle larger quantities of products. On the other hand, decentralization may require competent staff in remote areas, who can be difficult to find. These effects need to be considered at the time of designing a network and moving from centralized to decentralized systems or vice versa.

* 1. **Advantages of centralization**

The benefits of centralization in the blood supply chain are documented in the literature 21 22. Economy of scale is a key driver of centralization. Building and maintaining blood supply chain infrastructure is expensive. When cost can be allocated over a large number of units, economies of scale favor large production centers; the cost of a blood unit processed in a large blood center can be 40% lower than a unit processed in a small blood bank23. Reduction in safety stock is another advantage of centralization. From inventory theory it is known that safety stock should be proportional to demand variability. If it is possible to operate fewer, larger distribution centers, with less variability, less safety stock is required. Centralization also decreases wastage, since inventories tend to flow more freely between supply and demand nodes. Centralized supply chains also require fewer physical assets. In Colombia, 48% of BSC facilities produce less than 5000 units annually 24. Finally, centralized systems prevent duplication of services and eliminate competition for donors and customers between different agencies within a region.

* 1. **Advantages of decentralized systems**

Many examples of decentralized BSCs can, however, be found. Most are in developing countries, such as Brazil, where 530 blood banks collected 3.3 million blood units in 2012 or as in Venezuela where 316 blood banks collected 445,000 blood units in the same year25. In developed countries, such as the US, only 79 blood centers are needed to serve a population of 330 million26. The reasons for retaining a decentralized design differ from country to country, though large distances, high transportation costs and geographic remoteness tend to favor decentralized systems. Transportation difficulties may simply dictate a requirement for local blood centers to avoid the risk of stockouts. Decentralized networks, furthermore, provide local economic development and generate employment opportunities within regions. Finally, in some jurisdictions, the presence of competing agencies may make centralization difficult to implement.

* 1. **Summary**

Centralization of the blood supply chain has multiple benefits. Ignoring the political aspects, centralization decisions are dominated by geography, particularly with respect to the location of facilities. The approach proposed here supports decisions such as the optimal number and capacity of blood facilities, including collection, production and distribution centers, whether for centralized or decentralized systems.

1. **MATERIALS AND METHODS**

To find the optimal configuration of the blood supply chain and an optimal collection and production strategy, we employ a technique called mathematical programming. A mathematical programming model consists of decision variables that represent the decisions to be made, and constraints that make the model logically consistent. The solution to the model provides optimal values for the decision variables that maximize or minimize one or more objective functions (targets). A typical objective function in the blood supply chain is the minimization of total cost. A schematic representation of our model is presented in Figure 2.

Figure 2 here

* 1. **Decision variables**

The decision variables in our model (shown in Figure 2) relate to decisions in three of the four echelons of the blood supply chain. At the collection stage we include decisions on the location and capacity of collection centers; this also includes the number of apheresis machines needed to meet RBC and platelet apheresis requirements. At the production stage, the decision variables define the location and capacity of blood production centers, as well as the number of units to be processed in each center. Finally, in the inventory and storage stage, we consider the location and capacity of distribution centers. At this level, the allocation of demand zones to distribution centers is determined, but, as mentioned in the Introduction, the distribution stage is not modeled in detail.

* 1. **Objective function**

In our model, the objective is to minimize costs over a one-year period. The costs considered in our model are presented in Figure 2. This cost function comprises the fixed costs for the facilities, variable collection and production costs, variable handling costs, and inventory and transport costs, as well as penalties for stockouts. Fixed costs for facilities include a setup cost associated with the physical facility and a step-cost based on the capacity chosen. For collection centers, capacity is measured in number of donors; at the production stage, capacity refers to whole blood units; and for distribution centers, capacity refers to individual products.

The model is a proof-of concept, and therefore some broad assumptions are made, mainly due to a lack of detailed data. Staffing costs (salaries) are included in this step-cost but in reality would also be a component of the variable costs. Variable costs include the collection cost per donor for each collection method, and the production cost per unit processed. At distribution centers, variable costs include both the cost of keeping inventory and the handling cost for units dispatched. Finally, we include the costs of transporting the required units of blood between different stages.

To apply the model to a specific case, appropriate cost data must be used. Since the aim of this paper is to present a generally applicable approach to the design of any blood supply chain, the costs used in our case study example were all obtained from information in the public domain. The fixed cost data were obtained from [PAHO](#_ENREF_24) 23 and adjusted where necessary. Transport costs were assumed to be a function of travel time ($0.5/hour), and were obtained using Google Maps. Variable costs were extracted from [PAHO](#_ENREF_24) 23; inventory cost and handling cost were assumed to be a percentage of the value of the product.

* 1. **Constraints**

Decisions about the design supply of the blood supply chain must meet numerous practical and regulatory constraints. The model proposed in this paper contains the following assumptions: we recognize that many of these are oversimplifications, but the corresponding parameters could easily be modified in practice if more detailed data were available.

* Demand is defined in terms of population size in each geographical region, and is not only variable but also unknown in advance.
* Collection, production and distribution are limited to a predetermined capacity.
* Handling costs are a fixed percentage of the product cost.
* The total number of products obtained is adjusted by a historical discard rate, to take account of blood which fails quality tests.
* The maximum travel distances between the different stages are predefined by the decision-maker.
* Stockouts are highly undesirable, and are heavily penalized in the model at $1000 US per unit. As this is a strategic-level model, stockouts are not “real” stockouts that would occur in practice, but a reflection of overall lack of capacity to meet demand. The $1000 is therefore not a real cost, but a modelling device to favor strongly those solutions in which demand is fully met.
* Apheresis collection processes can be carried out in whole blood collection centers only.
	1. **Solution method**

The model described in Sections 3.1 to 3.3 can be solved exactly, using mathematical methods, assuming fixed demand. However, in reality demand is not fixed, and thus any solutions obtained from such models may not be valid in practice. Our model therefore considers uncertainty in demand. The approach is based on a technique called Sample Average Approximation (SAA) which simultaneously analyses multiple scenarios27 generated by sampling from probability distributions.

This approach has been widely used for industrial supply chain optimization. However, including multiple scenarios at the same time makes the model very difficult to solve, especially for large systems. For this reason, we propose a heuristic or approximate method based on the SAA approach that allows near-optimal solutions to be obtained in reasonable computation time. In general terms, the heuristic solves the model for individual scenarios and looks at “good” and “bad” locations, based on the number of times each location appears in the individual scenarios. These decisions are then fixed and the model is solved again considering all scenarios simultaneously. A fuller, more technical explanation and the mathematical representation of our approach can be found in [Osorio](#_ENREF_32)28.

* 1. **Data and case study**

The blood supply chain in Colombia consists of 82 blood banks and 414 transfusion providers, distributed across 32 regions and the capital, Bogota. The high level of decentralization means that indicators such as the outdating rate and cost are likely to be higher than for more centralized systems. In Colombia, the network comprises many different agencies, including public and private blood centers.

Another feature of the Colombian system is the difference in collection strategies throughout the country. Each region defines its own collection goals for blood and blood products using local decision rules. For example, the highest proportion of platelets collected by apheresis in 2012 was in the Valle del Cauca region at 93%, followed by Antioquia at 42%. However, most regions obtain platelets from whole blood donations.

In our model we consider 32 potential locations for collection and production centers, corresponding to the 32 regional capital cities, and 36 potential locations for distribution centers, based on the current location of blood banks. We grouped the 414 transfusion centers by city and considered 120 demand points. The data used is in the public domain (Instituto Nacional de Salud 29). The probability distributions for annual demand are assumed to be triangular, since there was not enough information available to apply statistical procedures to fit a probability distribution.

We assume that exactly 4% of the population will donate blood, based on historical donation rates from this population. In practice, this percentage may differ between regions, but in the case study we assume it is uniform throughout the country.

* 1. **Scenarios studied**

As mentioned in Section 1, our approach is flexible and thus allows several features such as uncertainty, and preferences to be modeled with relatively few modifications to the original mathematical framework. We compare network configurations with different levels of centralization, by varying the maximum travel times allowed between the different stages.

Seven different scenarios are studied, as shown in Table 2. The maximum times between collection and production reflect the regulations that apply in Colombia, but could easily be adapted for other countries. In the set of scenarios we consider the impact on the supply chain network configuration of assuming different maximum permitted travel times between stages. The travel time between production and distribution centers is constrained in Scenarios S1 and S2, but in Scenarios S3 - S7 it is not limited (this is denoted by the letter M) and thus the model will define the location and capacity of production centers based solely on cost. Scenarios S1 to S7 reflect increasing levels of centralization.

Table 2 here

The model can also consider several other design features, independently or in any combination, for example:

* The optimal design of the network given a fixed budget;
* The optimal design of the network for decentralization constraints;
* Optimal collection, production and distribution strategies for a pre-defined network;
* The impact of increasing the percentage of donations for each or all of the collection centers.

In addition, we have included service levels based on inventories and lead times. We consider two types of inventories. Firstly, cyclic inventory is the inventory available to cover the normal operation of hospitals. On the other hand, we have also included safety stock in order to have enough products to cover variations in demand. In terms of lead times, we have modelled hard constraints concerning delivery times between collection and production centers, production and distribution centers as well as distribution centers and demand zones.

Finally, we note that policies such as stock rotation and lateral transshipments are not included in the model. These are normally operational decisions to avoid expired units, rather than strategic decisions.

1. **RESULTS**

Table 3 presents detailed results of the application of the model to the demand data for the case study. We choose Scenarios S1 and S7 to draw insights from the results, since these represent the extremes of decentralization and centralization respectively.

In Scenario S7, with the longest travel times permitted, only 10 collection centers, 5 production centers and 13 distribution centers are needed, in contrast to 17, 15 and 22 respectively for the most decentralized scenario, S1. The number of donors is lowest in Scenario S1, but this scenario results in the highest number of stockouts because several remote regions have very low populations and cannot supply enough blood without violating the distance constraints. It should be noted that the total capacity required, for production and elsewhere in the supply chain, is greater for Scenario S1 than for S7; however, since the number of donors is lower, this capacity is used less efficiently in this scenario.

Table 3 here

Figure 3 compares results of Scenarios S1 and S7 geographically. Yellow (lighter) icons show locations where both a production center and a distribution center are recommended. Red (darker) icons represent distribution centers only and small green circles are demand points.

Figure 3 here

On the other hand, Table 4 presents an optimal collection rate for each collection center under Scenario S7. The aggregated, or national, collection strategy indicates that 37.9% of the blood should be collected using triplex bags, with 61.8% using quadruple bags, and the remaining 0.3% of donors assigned to RBCs by apheresis. However, the collection strategy varies for the different collection centers. For example, the percentages for the blood collection center located in Medellín are 40% and 60% for triplex bags and quadruple bags respectively; in Pereira, results are 64% and 36% respectively.

Table 4 here

As shown in Table 4, the solution obtained for Scenario S7 recommends the acquisition of two RBC apheresis machines for the Cartagena and Cali collection centers. This occurs in Cartagena because of the constraint on the maximum percentage of donors in the region. In contrast, in Cali the available number of donors could cover this constraint, but it would be necessary to expand the capacity by 10,000 units, which is more expensive than obtaining the same number of RBCs using apheresis. However, the number of donors allocated to this process is low in both locations and thus the decision-maker might consider whether simply to increase whole blood collection capacity in the region is more practical. Note that we have used a step capacity of 10,000 units in this example, but this can be altered to suit local conditions.

In addition, results include the optimal separation strategy for each production center. In Table 5, the optimal separation strategy nationwide with Scenario S7 is shown to be 89% for alternative A quadruple bags (RBCs, plasma, and platelets) and 11% for alternative B (RBCs and cryoprecipitate). These values are similar for all production centers.

Table 5 here

1. **DISCUSSION**

In this paper we have presented a generic model for finding an optimal configuration of a blood supply chain network. The model can be applied in any setting and incorporates features that were not included in previous models in the literature.

In its most general form, the model assumes that it is possible to redesign the blood supply chain from scratch. Obviously, this is unrealistic in practice, but the model can be easily modified to incorporate existing facilities and constraints (e.g. regulatory, geographical or economic) in any real-world system.

One of the important aspects of the model is the *a priori* selection of a set of feasible locations for facilities, depending on the type of facility. For example, the location of collection centers should take account of aspects such as accessibility. Access to main roads is important for production centers, given the high frequency of inbound and outbound transport. The same applies to distribution centers, but here it is also necessary to consider demand for emergency orders. In terms of implementation of redesign projects in the blood supply chain, the evidence from Canada and the UK suggests that the centralization process has taken place in stages. Thus, any reconfiguration of the network will usually be a gradual process.

Centralization of collection centers is less feasible than at the production stage, since it is unrealistic to expect donors to travel long distances. From a centralization point of view, the location of blood production centers is influenced by the travel time between collection centers and distribution centers. This means that in smaller countries with shorter travel times, centralization can be particularly attractive. The location of distribution centers depends on the required service level to demand points and thus is determined by the frequency and volume of periodical orders from hospitals as well as their location.

In practice, the model is a decision-support tool and is, to some extent, a “black box”. The model can inform decisions and provide impartial quantitative evidence, but model solutions must be carefully analyzed and interpreted in context by human decision-makers. The solutions returned are based on the information and constraints given to the model; however, in real life constraints can sometimes be relaxed and thus several different solution scenarios could be envisioned.

Finally, the model presented here can be applied anywhere in the world, regardless of process design, number of actors involved, or geography; the objective function, decision variables and constraints can be tailored for a wide range of systems including both centralized and decentralized blood systems. We therefore suggest that this framework represents an important development in models for blood system design and operations.

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Table 1. Quantity of units of blood products obtained when the different collection methods are used.

Table 2. Scenarios studied based on maximum travel time (in hours)

Table 3. Summary of solutions obtained under different scenarios on maximum travel time.

Table 4. Optimal collection strategy for each collection center, Scenario S7, “Centralized”.

Table 5. Optimal separation strategy for quadruple bags, Scenario S7

Figure 1. Location of blood production centers in (a) Colombia and (b) England.

Figure 2. Schematic representation of the mathematical model for the design of the blood supply chain

Figure 3. Geographical representation of the facility locations under (a) Scenario S1 (decentralized), and (b) Scenario S7 (centralized).

Table 1

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **No.** | **Process** | **RBCs** | **Plasma** | **Platelets** | **Cryoprecipitate** |
| 1 | Triplex bag | 1 | 1 |   |   |
| 2 | Quadruple bag (A) | 1 | 1 | 1 |   |
| 3 | Quadruple bag (B) | 1 |   |   | 1 |
| 4 | RBCs by apheresis | 2 |   |   |   |
| 5 | Platelets by apheresis |   |   | 1-2 adult doses\* |   |

\*This amount is approximately equivalent to the quantity obtained from 10 units of whole blood

Table 2

|  |  |
| --- | --- |
| **Maximum travel time** | **Scenarios** |
| **Decentralized ……………………………………...Centralized** |
| **S1** | **S2** | **S3** | **S4** | **S5** | **S6** | **S7** |
| **From CCs to PCs (hours)** | 3 | 4 | 3 | 4 | 3 | 4 | 5 |
| **From PCs to DCs (hours)** | 3 | 4 | M | M | M | M | M |
| **From DCs to DPs (hours)** | 3 | 4 | 3 | 4 | 5 | 5 | 5 |

CCs = Collection centers; PCs = Production centers; DCs = Distribution centers; DPs = Demand points; M = No constraint.

Table 3

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Decision | S1 | S2 | S3 | S4 | S5 | S6 | S7 |
| Collection Centers | Number | 17 | 15 | 9 | 10 | 11 | 11 | 10 |
| Number of capacity packages required, WB | 68 | 67 | 66 | 66 | 67 | 67 | 67 |
| Apheresis RBCs equipment | 3 | 4 | 2 | 2 | 2 | 2 | 2 |
| Apheresis platelets equipment | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Production centers | Number | 15 | 10 | 5 | 4 | 5 | 5 | 5 |
| Number of capacity packages required | 69 | 67 | 66 | 66 | 67 | 67 | 67 |
| Distribution Centers | Number | 22 | 18 | 23 | 17 | 13 | 13 | 13 |
| Number of capacity packages required | 114 | 111 | 114 | 111 | 112 | 112 | 112 |
| Average number of donors required | Triplex bag (thousand) | 236 | 241 | 245 | 248 | 252 | 253 | 252 |
| Quadruple bag – A (thousand) | 349 | 361 | 358 | 361 | 365 | 365 | 365 |
| Quadruple bag – B (thousand) | 43 | 45 | 45 | 45 | 45 | 45 | 45 |
| RBCs by apheresis (thousand) | 3 | 5 | 1 | 1 | 2 | 2 | 2 |
| Platelets by apheresis (thousand) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Average total donors (thousand) | 632 | 651 | 649 | 655 | 664 | 665 | 665 |
| Average stock outs (thousand) | 49 | 16 | 24 | 16 | 0 | 0 | 0 |
| Average cost ($ million) (without stock outs) | $36.5 | $35.6 | $34.4 | $34.3 | $34.7 | $34.6 | $34.6 |

WB = Whole Blood

Table 4

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Collection Center** | **Maximum donor population****(thousands)** | **Number of donors required****(thousands)** | **Collection Process** | **Number of bags to be processed by production center (thousands)** |
| **Medellín** | **Barranquilla** | **Bogotá, D.C.** | **Bucaramanga** | **Cali** | **Total** | **%****per process** |
| Medellín | 98.57 | 98.57 | Triple Bag | 39.43 | 0 | 0 | 0 | 0 | 39.43 | 40% |
| Quadruple Bag | 59.14 | 0 | 0 | 0 | 0 | 59.14 | 60% |
| Barranquilla | 48.73 | 48.73 | Triple Bag | 0 | 18.79 | 0 | 0 | 0 | 18.79 | 39% |
| Quadruple Bag | 0 | 29.94 | 0 | 0 | 0 | 29.94 | 61% |
| Bogotá, D.C. | 315.1 | 309.7 | Triple Bag | 0 | 0 | 99.63 | 0 | 0 | 99.63 | 32% |
| Quadruple Bag | 0 | 0 | 210.0 | 0 | 0 | 210.0 | 68% |
| Cartagena | 40.07 | 40.02 | Triple Bag | 0 | 21.15 | 0 | 0 | 0 | 21.15 | 53% |
| Quadruple Bag | 0 | 18.50 | 0 | 0 | 0 | 18.50 | 46% |
| RBCs by apheresis | 0 | 0.371 | 0 | 0 | 0 | 0.371 | 1% |
| Popayán | 11.10 | 10.00 | Triple Bag | 0 | 0 | 0 | 0 | 4.747 | 4.747 | 47% |
| Quadruple Bag | 0 | 0 | 0 | 0 | 5.253 | 5.253 | 53% |
| Cúcuta | 26.00 | 17.63 | Triple Bag | 0 | 0 | 0 | 14.44 | 0 | 14.44 | 82% |
| Quadrup Bag | 0 | 0 | 0 | 3.182 | 0 | 3.182 | 18% |
| Armenia | 11.86 | 10.00 | Triple Bag | 0 | 0 | 0 | 0 | 4.192 | 4.192 | 42% |
| Quadruple Bag | 0 | 0 | 0 | 0 | 5.808 | 5.808 | 58% |
| Pereira | 18.78 | 18.39 | Triple Bag | 0.322 | 0 | 0 | 0 | 11.50 | 11.82 | 64% |
| Quadruple Bag | 0.204 | 0 | 0 | 0 | 6.365 | 6.569 | 36% |
| Bucaramanga | 21.11 | 20.00 | Triple Bag | 0 | 0 | 0 | 4.320 | 0 | 4.320 | 22% |
| Quadruple Bag | 0 | 0 | 0 | 15.68 | 0 | 15.68 | 78% |
| Cali | 94.79 | 91.43 | Triple Bag | 0 | 0 | 0 | 0 | 33.56 | 33.56 | 37% |
| Quadruple Bag | 0 | 0 | 0 | 0 | 56.43 | 56.43 | 62% |
| RBCs by apheresis | 0 | 0 | 0 | 0 | 1.433 | 1.433 | 2% |
| **National** | **686.1** | **664.5** | **Triple Bag** |  |  |  |  |  | **252.1** | **37.9%** |
| **Quadruple Bag** |  |  |  |  |  | **410.6** | **61.8%** |
| **RBCs by apheresis** |  |  |  |  |  | **1.804** | **0.3%** |
| **Total** |  |  |  | **99.09** | **88.76** | **309.7** | **37.63** | **129.3** | **664.5** |  |

Table 5

|  |  |
| --- | --- |
| **Production Center** | **Separation strategy** |
| **Total quadruple bags****(thousand)** | **Alternative A****(thousand)** | **%** | **Alternative B****(thousand)** | **%** |
| Medellín | 59.34 | 52.82 | 89% | 6.518 | 11% |
| Barranquilla | 48.44 | 44.41 | 92% | 4.027 | 8% |
| Bogotá | 210.0 | 184.4 | 88% | 25.67 | 12% |
| Bucaramanga | 18.86 | 17.17 | 91% | 1.692 | 9% |
| Cali | 73.86 | 66.58 | 90% | 7.277 | 10% |
| **National** | **410.6** | **365.4** | **89%** | **45.18** | **11%** |





(a) Colombia (200 km Google maps view) (b) England (100 km Google maps view)

Figure 1



Figure 2





1. Scenario S1 (b) Scenario S7

Figure 3