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A hybrid matheuristic approach for the integrated location routing problem of the pineapple supply chain

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A B S T R A C T

This paper proposes a matheuristic approach for the location-routing of industrial platforms of the pineapple supply chain problem. We have proposed a three-phase methodology to solve the considered problem. The first phase consists of obtaining the potential supply in terms of suitability and productivity, the potential location of platforms, and the times of the value chain echelons. In the second phase, a mathematical optimization model for the location problem of platforms considering the coverage in terms of timing is proposed. Finally, the final phase proposes a cluster-routing and a granular reactive tabu search approach for the routing phase. The proposed methodology uses official information on production times, speed, and capacity and georeferenced aptitude, spatial, economic, and land yield information for the first time. The proposed approach has been validated through scenarios, particularly pineapple exports for the Colombian country. The obtained results show the efficiency of the proposed approach.

1. Introduction

After decades of efforts focused exclusively on internal armed conflict, Colombian national institutions are transitioning toward investing in agribusiness development under conditions of legality and sustainability. It is vital to exhaust efforts in the development of competitiveness in a context of circumstantial disadvantages compared to the ecosystems and logistic components of homogeneous countries to carry out the ambitious commitments and objectives proposed in this field as state policies by the government in power, which present advantages based on know-how (Asohufrucol, 2023). Within the effective transformation program (PTP) of Bancoldex, the idea of logistics centers as industrial management platforms (IMPs) is proposed, which are not limited to intermediation in fruit and vegetable logistics chains but contribute comprehensively and systematically to the evolution of the sector. An IMP can be as complex as the claims established a priori, so it is of great relevance to analyze their different objectives, functions, added values, constitution characteristics, and the obstacles present in the location. One of the cases of success in Colombia is Cartama®, which was formed in 2000 in Pereira under the vision of business opportunities and the expected boom in Hass avocados in the coming year (Gomez et al., 2019). On the other hand, Bengala® was formed in 2012 under the vision of diversification of the investments of the Riopaila® Complex and Castilla®. In 2017, Colombia achieved a productivity of 120 tons/ha, which is highly successful considering that it is similar to that of the leading countries in the region (Franco & Barona, 2019). Consulting firms have proposed trivial procedures to interpret the growing demand for pineapple in the world through a direct relationship between the political and demographic growth of the population and high-quality fruit and vegetable consumption (Asohufrucol, 2023). Additionally, the evolution in the balance of classes with greater purchasing power and the growing demand for healthy production proposes an optimistic scenario for the future. Growing and stable demand is vital when proposing a business model such as an IMP, whose financial balance is profitable and better-remunerated for all links in the chain, especially for small growers.

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The benchmark country on the American continent is Costa Rica, mainly in terms of market capture, income, and productivity per hectare. This issue is a country in development, restricted in area and with limitations in infrastructure; despite this, it exploited the business model to position itself effectively. The competitive advantage that stands out in this case of success is the standardization of the processes and the good practices acquired. On the other hand, the most representative weaknesses are poor field-industry integration and the scarce implementation of adequate innovative equipment for fresh products and byproducts. This study collects the experiences of international leaders in the production of pineapple and the information of the leading national companies, not only to stimulate the production scenarios but also to configure the chain, starting from the optimal localization of the IMPs.

This paper aims to develop an efficient solution method for the location-routing problem of the logistic platforms for the fruit product Ananas comosus (pineapple) with an export focus in rural areas of industrial management, based on a three-phase methodology. The first phase determines the supply chain's demand and potential supply, calculating the demand and offer data and the potential transfer points. The second phase proposes a mathematical model for the location phase of the platforms. Finally, the third phase proposes a routing scheme combining cluster techniques and a granular reactive tabu search. This fact differs from the multicriteria tools proposed by foreign trade banks, which have championed studies in this area of knowledge.

Section 2 describes the considered problem—and section 3 details the proposed methodology, explaining each phase. The computational results are shown in Section 4. Finally, Concluding remarks are described in Section 5.

2. Description of the problem

The Colombian fruit and vegetable sector is in an advantageous position because it has suitable agrological and environmental conditions for a wide range of crops and, in addition, can generate harvest conditions throughout the year through meteorological characteristics and geographic location. The trend of pineapple planting in Colombia has grown steadily in recent years at an average rate of approximately 6% year by year; however, the yield has not presented substantial growth, with a rate of 3.2%, which implies a low development in productivity (Ministerio de Agricultura y Desarrollo Rural, 2017). In 2016, national productivity was 41.19 tons/Ha, which is far from an example of success such as Bengala®, which reached a value of 65 tons/Ha in the year (Ministerio de Agricultura y Desarrollo Rural, 2017).

For any developing country, there are obstacles to achieving success in any business model. Despite all the related difficulties, Colombia occupies tenth place worldwide in producing A. comosus and has reached seventeenth place in exports (Tridge, 2018). The exports in 2017 were performed to 24 countries on four continents, at 16.68 million tons and a monetary value of 10.5 million dollars. Currently, Colombia has five varieties of pineapple for domestic and foreign markets: Giant pineapple, Queen pineapple, Honey pineapple (Tainung), Green Selangor pineapple, and Reina Malacca pineapple (Tridge, 2018). Of these, the most often exported is Honey. Colombia has essential strengths that should be exploited to improve productivity indicators, capture a more excellent supply of the world market, and improve the results described above (Asohufrucol, 2023):

- Strategic location for cultivation.
- Export by two seas.
- Attractive destination for investors.
- Supply of labor.
- Concentration of specific knowledge.
- Increase in export-type production.
- Availability of fertile land for cultivation.

Pineapple has desirable parameters at the time of sale, and its aesthetics and health benefits are generally sought. Next, some of the characteristic attributes of the fresh product demanded by international customers are described.

- Color of the bark: Represents the color of the peel of the pineapple in its process of evolution from green to yellow, reflecting the maturity of the fruit. In Colombia, a scale from 0 to 6 is used.
- Size: Indicates the weight and standardized size on a scale of 5 to 10.
- Shape, firmness, and defects: The pineapple should be slightly conical, from 1000 to 2500 grams. The uniformity of the shoulders or sides of the crown is fundamental for its approval.

The problem consists of determining the platform location and the routing decisions related to the distribution of the pineapple, considering the real data problem.

3. Proposed methodology

The proposed approach solves the above-described problem considering three phases, which are detailed below.

3.1. Phase 1: Obtaining the offer and the potential transfer points

3.1.1. Offer of pineapples

The land evaluation scheme integrates and analyzes the physical, ecological, and socioeconomic components proposed in the Framework for Land Evaluation (FAO, 1976) to optimize planning in the field. The definition of land units (farms) and crop requirements is associated with a multicriteria analysis according to the qualification and data processing of the most relevant criteria in an agricultural business model.

The criteria are a group of conditions that establish aptitude for specific use in a rural area and are classified into four groups: hierarchical, technical exclusions, legal, and conditional exclusions. A hierarchical criterion of analysis increases or reduces the suitability of commercial pineapple cultivation. Technical exclusion criteria regard the areas that are not feasible for cultivation due to physical or socio-ecosystem conditions. Conditional criteria refer to those areas that require additional studies to verify the feasibility of the crop regardless of their attitude. Finally, legal exclusion criteria delimit the areas that do not allow agricultural development. A cartographic map of zoning suitability for the pineapple is generated (see Fig. 1).

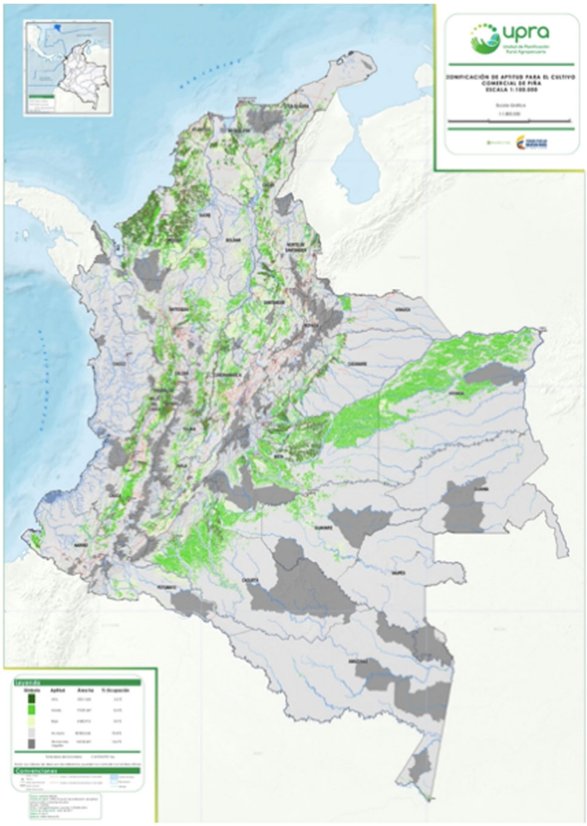

Fig. 1. Municipalities for pineapple products. Source (UPRA, 2017)

Only the area with high suitability zoning in the national territory is used to evaluate the scenarios with the most significant impact on obtaining pineapple production. On the other hand, the products applied to the planted area are higher than the national average but conservative compared to the case of success.

The methodology used to calculate production is as follows:

1. The area with high suitability by a municipality is obtained from the intersection of information.
2. Based on the municipalities with high suitability and their respective determined areas, the product is produced with the minimum productivity of Bengala® from when it entered the *A. comosus* business. The operation described above is the production in tons per municipality.

3.1.2. Transfer point of pineapples

Pineapples show the degradation characteristic of perishable products. For IMP coverage to be sufficient, it is necessary to know the maximum time available to verify the export feasibility. In the study carried out in Franco & Barona (2019), important information was reported to estimate the maximum transport times of *A. comosus*.

From the analysis of the study, it was possible to obtain the behavior of the peel color at four-time points of analysis: 30, 50, 70, and 90 days under special temperature conditions. All markets have different color requirements depending on their emphasis; however, during the study, it was elucidated that, from experience, the preferred peel color for pineapple exportation is two. Based on the experts' information and the fruit's behavior, an interval of 50 days is used for two reasons: it preserves the least amount of fruit in colors greater than two (national market). It presents a considerable amount of time available for transport.

Simulation models arose from the need-to-know behaviors and supported them with a reliable tool rather than by the approximate estimates of a person. According to Costa Rican literature (Unidad de Planificación Rural Agropecuaria, 2017), the sequence of the standard operations is created to obtain a time per capacity of a truck of 8.5 tons (assumption of transport to the IMP, based on that used by Bengala® and Cartama®). The average result for pineapples is 16.9 hours, and the maximum is 32.9 hours. The maximum value is used to manage a conservative profile at harvest. It is impossible to continue working 32.9 hours; therefore, a workday of 9.6 hours per day is considered; consequently, the maximum would require 3.42 days. The factor used to compensate for the high-temperature conditions, which are very harmful to the fruit, is five days of refrigeration each day at room temperature, for a total of 17.1 days. Note that seven resources (workers) are assumed to be used for the different tasks for the above processing.

The simulation model of the IMP is based on the Costa Rican literature and is complemented by the study of the Bengala® plant presented in Franco & Barona (2019). The process begins with loading pineapple into bins with 1200 kg from a van from the production unit or farm. Subsequently, unloading is performed in what is known as an immersion pool, where washing, disinfection, and fumigation are performed in addition to analyzing the specific gravity of the fruit. Subsequently, the fruits are transported individually on an automated belt, from which several pineapples are randomly selected for laboratory tests. At the same time, the rest of the production continues without interference with preselection by shape and size.

Part of the product is withdrawn for the national market through preselection (primarily based on aesthetic characteristics), and the rest continues with the conveyor belt, going through a waxing process and, in some cases (not all the packing plants apply this), receiving a second layer of fungicide. Next, the fruits are organized in the required direction for the subsequent automatic classification by size in three workstations, where they are manually placed in standardized boxes for export. Then, the boxes are placed again on the conveyor belt, wherein parallel markings are applied at the base and the crown. At this point, the stage on the conveyor belt is completed; a pallet is formed with a quantity of 64 boxes (standard commercialization unit) and then transported to refrigerated storage at seven °C. Whenever 21 pallets have been obtained, the 40-foot refrigerated container destined for the port is loaded.

The results based on the model include the production of 17.8 tons in 16.43 hours of work in two shifts, which is typical for an IMP. Fifteen resources (workers) are used for the different tasks to obtain these results. Since the Colombian road infrastructure is limited and does not present duality in the roads, through the Google application programming interface (API) and the budget available to obtain this information, it is possible to determine the distances and times between each pair of municipalities according to the best information from the search engine. This information is used in the optimization model to perform the two logistical trips required: the production unit to the IMP and the IMP to the maritime port.

The additional times at the ports and maritime transport are obtained from the public platform Searates®. Note two critical assumptions. The first is that the selected Colombian port is the one currently used by Bengala®, that is, the Port of Buenaventura. The second assumption is the destination port, where the Netherlands is selected in eighth place for national exports, a demanding and exciting location in maritime transport timing.

3.2. Phase 2: Optimization model for the location of platforms

The proposed mathematical model results from a composition of three classic models from the literature (location, set covering, and maximum flow), where the problem of the localization of the IMP is presented as a model of maximization of the profit given the operating costs and logistical costs. The proposed model uses a trained localization model (Medaglia et al.,2009) with a change like the variables to quantify the production sent from the municipalities to the logistics centers. Similarly, parameters are added to ensure coverage from the port to the platforms' possible locations, given the crop transfer time constraints. It is essential to clarify that the model is based on the localization of IMPs only in municipalities of high suitability (Unidad de Planificación Rural Agropecuaria, 2016).

The mathematical model of the location of the IMPs is presented, where the sets, parameters, variables, objective function, and restrictions are summarized.

Sets

M: set of municipalities of high suitability in Colombia

Parameters

t_{max}: maximum time for the optimal delivery color of product
t_{cl1}: available time for the municipalities-IMP routing
t_{cl2}: available time for IMP-port routing
t_{ocl}: operation time in the IMP
$t_{harvest}$: harvest operation time per truck
$t_{port-country}$: transit time in the port of Colombia
t_{ship}: transport time from port to port
$t_{port-destination}$: transit time at the destination port
t_{max}: $t_{harvest} + t_{cl1} + t_{ocl} + t_{cl2} + t_{port-country} + t_{ship} + t_{port-destination}$
t_{ij}: transportation time between municipalities $i \in M$ and $j \in M$
d_{ij}: transport distance between municipalities $i \in M$ and $j \in M$
p_j: production of municipality $j \in M$
cl_1: land logistics cost between municipalities and IMP
cl_2: land logistics cost between IMP and the port
C_o: cost of opening an IMP
$price$: product price
pmn: sale price of pineapple in the domestic market
U_{grow}: utility of the grower
CC_{grow}: grower cost
C_p: operating cost in the port
DC : Number of distribution centers to be opened

Decision Variables

$$x_j \begin{cases} 1 & \text{If an IMP is opened in municipality } j \in M \\ 0 & \text{Otherwise} \end{cases}$$

$$b_{ij} \begin{cases} 1 & \text{If the municipality } j \in M \text{ is covered from the IMP } i \in M \\ 0 & \text{Otherwise} \end{cases}$$

inv_j: product inventory in the IMP located in $j \in M$

y_{ij}: flow between municipality $j \in M$ to CD $i \in M$

Objective Function

$$\max \sum_{j \in M} \left[inv_j * price * 0.63 + inv_j * pmn * (1 - 0.63) \right] - \sum_{i \in M} \sum_{j \in M} \left(d_{ij} * cl_1 * y_{ij} \right) - \sum_{i \in M} d_{i-port} * cl_2 * x_i * inv_j - \sum_{i \in M} C_o * x_i - \sum_{j \in M} inv_j (U_{grow} + CC_{grow}) - \sum_{i \in M} C_p * x_i \quad (1)$$

Constraints

Covering constraints from IMP to the port

$$b_{j,port} \geq x_j \qquad \forall j \in M \qquad (2)$$

Inventory balance constraints

$$inv_j = \sum_{i \in M} y_{ji} \qquad \forall j \in M \tag{3}$$

Inventory constraints per IMP

$$\sum_{i \in M} y_{ji} \leq 17.8 x_j \qquad \forall j \in M \tag{4}$$

Production Capacity Constraints

$$\sum_{j \in M} y_{ji} \geq p_i \qquad \forall i \in M \tag{5}$$

Opening Distribution Centers (DC) constraints

$$\sum_{i \in M} x_i \leq DC \qquad \forall i \in M \tag{6}$$

Municipality covering constrains

$$y_{ij} \leq M * b_{ij} \qquad \forall i, j \in M \tag{7}$$

Nature of variables

$$y_{ij} \geq 0 \qquad \forall i, j \in M \tag{8}$$

$$inv_j \geq 0 \qquad \forall j \in M \tag{9}$$

$$b_{ij} \in \{0,1\} \qquad \forall i, j \in M \tag{10}$$

$$x_j \in \{0,1\} \qquad \forall j \in M \tag{11}$$

The essence of the optimization model is to locate the IMPs to ensure that the transfer time of the pineapple crop is sufficient for export and that the best financial results are obtained. The set covering of the segment consists of two equations. Equation 2 ensures limiting the number of feasible IMPs due to the distribution time from the IMPs to the port of Buenaventura. Similarly, Equation 7 delineates the feasible IMPs, in this case, from the bidding municipalities (collection). It is essential to clarify that the supply transport time has a more significant effect than the distribution transport since, during supply transport, the fruit is unrefrigerated and is affected; the exposure is taken into account in the harvest simulation model. The maximum flow segment represents the crop shipment from the municipalities to the IMPs. Equations 4 and 5 restrict the flows so that they are not more significant than the production of the municipality and are within the daily capacity of the IMP.

Finally, Equations 3 records the production of the platform. The third segment of the model is represented by the variable x_j, which decides which logistics centers should be opened and connects all the equations with Equation 1. Six costs present in the export of the crop and a sale price per ton produced are considered to construct the objective function (Equations 1). The first cost is the collection routing from the municipalities to the IMPs, determined through the application developed by the Ministry of Transportation SiceTAC (Ministerio de Transporte Colombia, 2018).

The methodology developed to estimate the average cost per kilometer traveled and ton transported generates routes between extreme municipalities in the country and estimates the average. In addition, a profit percentage of 50% for the transporters is added. The second term is the transportation cost from the IMPs to the port of Buenaventura, whose estimation is similar to the supply transport methodology, with the difference that these time routes are generated from all the municipalities enabled in the platform to the port. The third cost is opening the IMP, which is estimated by Bancoldex and extrapolated for the size of the platform, considering the installed capacity. This cost is estimated to be recovered in five years of operation, for which a daily opening cost of COP 8,307,945. The fourth cost is associated with the crop purchase from farmers, estimated by the association of producers, marketers, and agricultural processors, where they value an expense associated with the operation of the pineapple crop. A utility in the crop for farmers of 60% is added, considering the literature. The fifth cost is associated with the operation of the IMP and, like the opening cost, is an estimate made in the Bancoldex market research.

The optimization model also considers a price associated with selling the export-type crop. This price is taken from the historical prices of international sales of Colombian pineapple from the macroeconomic statistics consultancy. The model considers that not all areas of high suitability become crop producers, so a limitation of production is applied based on analysis scenarios. For 2016, the area of pineapple crops was at most 0.01% of the municipalities with high suitability. A delimitation of the production is made with two scenarios. The first scenario, called pessimistic, has production from 0.01% of the capacity of municipalities with high suitability, and the second scenario, called optimistic, has production from 1% of the total area of municipalities with high suitability. In the model presented in Equations 1-7, a series of assumptions are taken into account as follows: The production of the municipalities is collected in the center, but this is corrected in the routing stage of vehicles with maximum distance restrictions (the distance constrained vehicle routing problem (DCVRP)), using the polygons associated with the productive units within the municipality. The available time is divided equally for supply and distribution transport, given the transfer time. Fixed costs are not variable over time. The distances are calculated with the Google® API, where the times and distances depend on the traffic at the request. Different instances or scenarios of the problem are generated to review how the model results change and analyze its robustness. It is important to note that the selection of the scenarios is based on the importance of the model.

The first scenario is called "real" due to its similarity with the current national production of pineapple and based on the productivity of the IMP (17.8 tons/day) and the number of platforms that supply this product. The IMPs are located in the following municipalities: La Cumbre, Valle del Cauca; Agrado, Huila; and Pital, Huila. The locations in these municipalities are chosen because, first, they are highly suitable; that is, their opening is recommended under a physical, social, ecosystem, and financial analysis. Second, these municipalities are surrounded by nearby municipalities with high aptitude and the capacity to supply the maximum demand, which undoubtedly reduces logistical costs (see Fig. 2).

The pessimistic production scenario is proposed to analyze the model's behavior with a supply of 0.01% of the potential production. One IMPs presents a significant concentration of the supply of all available municipalities regardless of the distance to complete the platform's installed capacity. On the other hand, it is possible to elucidate that the two IMPs are located far from the ports are in a state of "risk" because, in the distribution transport, it may not be possible to meet the transfer times, remembering that transport without refrigeration penalizes the attributes of the fruit. The second IMP is located far from the first to cover the supply available in the country. The platforms are in the Buenavista and Zarzal municipalities (see Fig. 3).

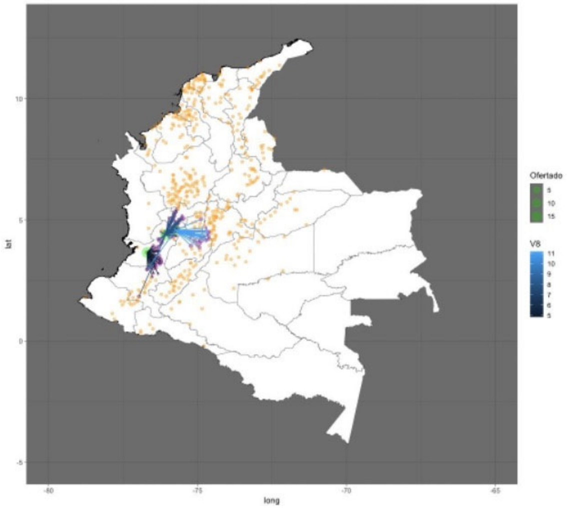

Fig. 2. Scenario with number of IMP according to national exports.

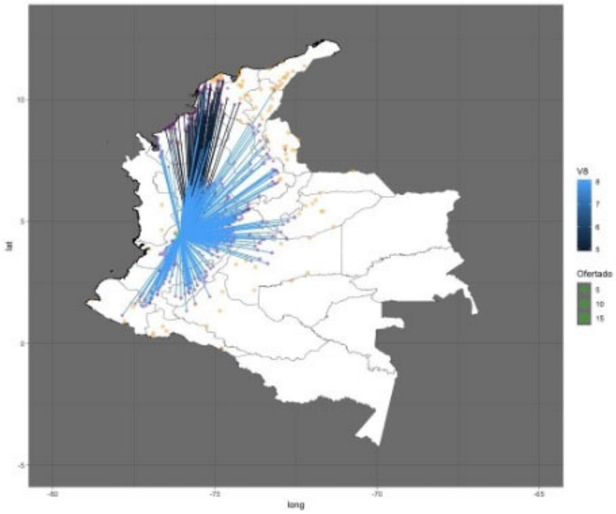

Fig. 3. Pessimistic scenario in pineapple production.

The optimistic production scenario is proposed to analyze the model with a supply of 1% of the potential production presented by the municipalities with high suitability. This scenario is ideal because a large part of the potential area is available to cultivate pineapple, which does not happen in the field since the uncertainty in the prices of perishable goods means that growers exploit their land under a multiproduct model. There is a high mobilization of pineapple cargo from the north to the country's center due to excess production. Because the municipalities have high production, opening an IMP near the port is feasible without using the maximum installed capacity. Similarly, municipalities also cannot care for themselves, so logistical costs are highly reduced (see Fig. 4).

A scenario with time constraints and optimistic production is proposed to analyze the model with a substantial constraint on the transfer time of the product. The routes are short, except for three that transport from a region with high suitability to the country's center, whose location is strategic for transport to the port. Large concentrations of supplying municipalities are observed. Similarly, when there is a decrease in transport coverage, regions that are not feasible are visualized, leaving part of northern Colombia as a source of exports due to its high suitability concentration and the center of Colombia due to its proximity to the port. The platforms are located in 12 municipalities very close to the port of Buenaventura (see Fig. 5).

A scenario for analyzing logistic costs and neutral production is proposed to analyze the model with a constraint on the cost that can be improved through routing strategies. The results for the logistic cost are telling in the sense that significant changes are observed in the location of the IMP in the optimistic versus pessimistic scenarios. It is observed that the northern and eastern zones cancel the opening of the IMP since extensive routes are penalized. Despite the above, there is a fundamental factor: the fourth generation (known in Colombia as 4G) of road concessions in Colombia make a segment of the Caribbean zone remain a seductive location with high benefits. In other words, the time in these routes is shorter. On the other hand, since there is a high supply of aptitude, the first route is short, which generates logistical savings that increase the attractiveness of this region (see Fig. 6 and 7).

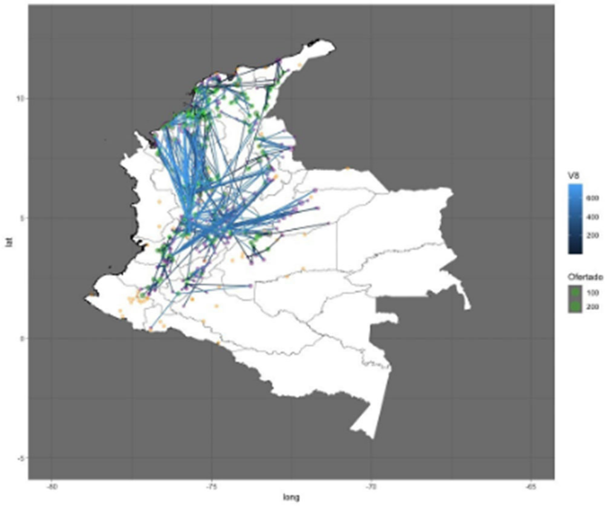

Fig. 4. Optimistic scenario in pineapple production

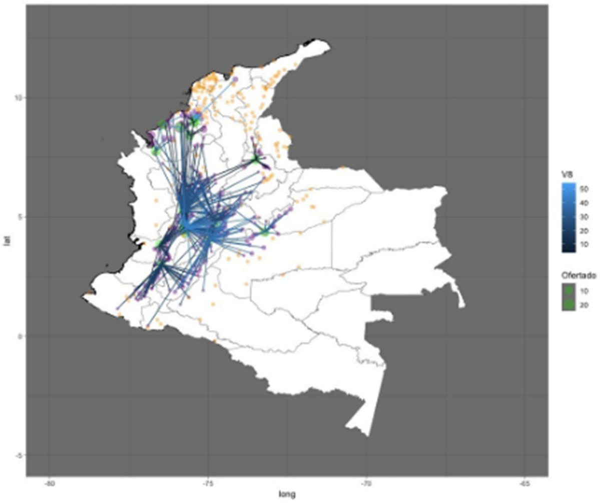

Fig. 5. Pessimistic scenario in the logistic cost and neutral production

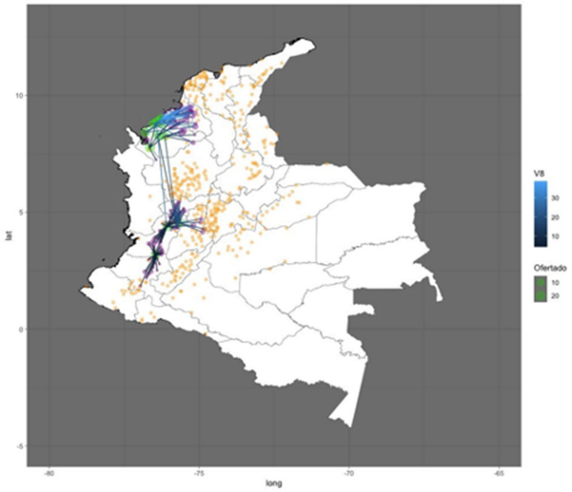

Fig. 6. Pessimistic scenario with logistic times and neutral production, that is, 0.1%.

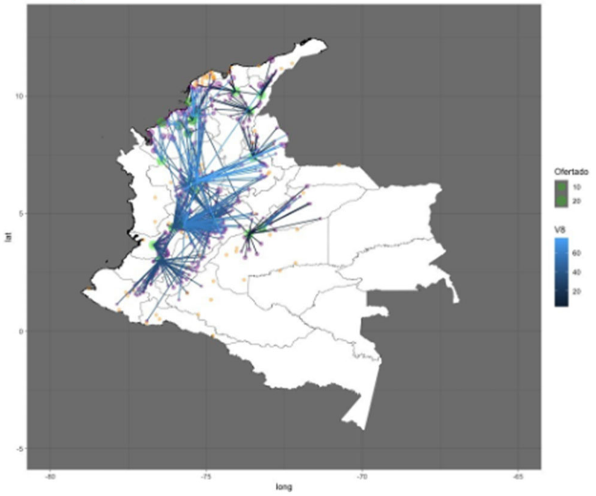

Fig. 7. Optimistic scenario in the logistic cost and neutral production.

3.3. Phase 3: Routing Scheme

After the locations of the IMPs and the municipalities, the storage route is determined, seeking savings in the pineapple transportation from the productive units (producing farms) to the areas to be served by the IMPs. This fact, as expected, increases the complexity of the problem since we move from a problem with a few hundred customers to one with thousands of customers. Therefore, we propose a metaheuristic algorithm based on an urgency cluster and a reactive granular tabu search (GTS) algorithm based on the main idea proposed by Toth & Vigo (2003) and Cordeau & Laporte (2005). The proposed clustering algorithm uses different levels of randomness, seeking to achieve a high degree of diversification that allows the GTS to find efficiencies in the collection routes. Therefore, clustering seeks to generate a competition of the IMPs for the productive units that are in the "borders" (polygons equidistant at least two IMP) to correct the solution obtained from the localization model since it is constructed only at the scale of municipalities to reduce the number of constraints that grow combinatorial for the routing problem of vehicles that collect freshly harvested fruit.

Algorithm 1. Urgency Cluster-Routing Algorithm

Inputs: *IPMs* list of the IPMs, *Municipalities* list of productive pineapple municipalities;
Parameter: *Urgencies* = $\{u_1, u_2, ..., u_m\}$ *m* levels of randomness, *N*: iterations for *Urgencies* training, *TotalIterations* number of iterations.
Output: *Incumbent* list of recollection routes.

```
1   for i = 1 to TotalIterations
2       for j = 1 to Municipalities
3           if i ≤ N then
4               Urgency ← randomly select an Urgency level with a uniform probability
5           else
6               Urgency ← randomly select an Urgency level with a probability $p_u$
7           end if
8           for k = 1 to IMPs
9               if k.distance ≤ $Farthest_{IMPs,j} - (Urgency \cdot (Farthest_{IMPs,j} - Nearest_{IMPs,j}))$ then
10                  Candidates ← AddIMPtoRestrictedCandidateList(k)
11              end if
12          end for
13          IMPselected ← SelectRandomly(Candidates)
14          Assignations ← AsignMunicipalityIPM(j, IMPselected)
15      end for
16      for each IPM assigned in Assignations
17          Routes ← GTS(IPM, Assignations, Municipalities, D, Q; Tenures, $\beta ethas$, N, GTSIterations)
18          Solution ← AddRoutes(Routes)
19      end for
20      if OF(Solution) ≤ OF(Incumbent) then
21          Incumbent ← Solution
22      end if
23      $OF_{urgency} \leftarrow OF_{urgency} + 1/OF(Solution)$
24      $p_u \leftarrow OF_{urgency} / \sum_{l=1}^{m} OF_l,\ \forall urgency \in Urgencies$
25  end for
26  return Incumbent
```

Urgency clustering is an adaptation of the nearest neighborhood heuristic, in which municipalities are randomly assigned to one of the nearest IMPs, considering the installed capacity of the logistics center when making the assignment (see Algorithm 1). This algorithm introduces a dynamic element by incorporating multiple levels of urgency, denoted as "urgencies." It operates over a set number of iterations (line 1), with an initial phase of urgency training (lines 3 and 4), after which the probability of selecting different urgency levels (lines 5 and 6) adapts based on the quality of solutions obtained (lines 23 and 24). In each iteration (lines 2 – 24), the algorithm first selects the urgency level (lines 3 – 7) and, with it, performs the pseudo-random assignment of municipalities to IMPs (lines 8 – 14); with this assignment, it resorts to the search granular tabu to find an efficient set of routes (lines 16 – 19) and checks if the current solution is of better quality than the incumbent solution and therefore it should be updated (lines 20 – 22). The algorithm will call only the best levels of urgency using a probabilistic selection process based on the performance quality obtained. Finally, the algorithm returns the pineapple collection routes stored in the incumbent solution (line 26).

Granular Tabu Search was selected to obtain a reliable collection route of freshly harvested fruit, trying to minimize the logistic costs. The GTS is selected due to its good performance in different works (Prins et al., 2007; Jin et al., 2012; Escobar et al., 2013; Bortfeldt & Homberger, 2013; Kirchler & Calvo, 2013; Escobar et al., 2014; Bernal et al., 2018). In particular, the GTS published by Bernal et al. (2018) is a fair point of comparison because it solves the same variant of the vehicle routing problem (VRP) that is required in this study (the DCVRP). The algorithm presented in this project begins its operation by determining a giant tour using the Lin–Kernighan–Helsgaun (LKH) heuristic for the traveling salesman problem (Helsgaun, 2000) without considering the travel center distribution. Then, based on a set partitioning model (Irnich et al., 2014), the IMPs are assigned to the productive units, and again, using the LKH heuristic, the routes that, in this case, already contain the IMP are refined.

Once the initialization procedure is finished, the local search heuristic is applied based on a GTS. Initially, a granular space is created by pruning all the arcs above a threshold determined by a selected factor and the average costs, obtaining an incomplete graph. Next, the algorithm chooses the best solution using the following intraroute and interroute operators: insertion, swap, two-opt, exchange, and double swap (Toth & Vigo, 2003). At this point, the heuristic prohibits the last movement from reaching this best neighbor during a certain number of iterations to avoid impacting the search process. Finally, a disturbance method is added to the code.

Algorithm 2. Granular Reactive Tabu Search

Inputs: *Depot* selected *IPM*, *Customers* assigned Municipalities, *Duration* maximum distance of the routes, *Q* vehicle capacity;

Parameter: *Tenures* = $\{T_1, T_2, ..., T_m\}$ *m* levels of tenures, $\beta ethas = \{\beta_1, \beta_2, ..., \beta_m\}$ *m* factors of sparsification, *N*: iterations for $\beta ethas$ training, *GTSIterations* number of iterations.

Output: *GRTSIncumbent* list of recollection routes for a selected IPM.

```
GiantTour ← LKH(Depot, Customers)
RoutesPool ← ClusteringContiguousCustomers(GiantTour, Duration)
CurrentSolution ← SolveSetPartitioning(Depot, RoutesPool)
for $i = 1$ to GTSIterations
    if $i \leq N$ then
        $\beta etha$ ← randomly select a sparsification factor with a uniform probability
        Tenure ← randomly select a tabu duration with a uniform probability
    else
        $\beta etha$ ← randomly select a sparsification factor with a probability $p_\beta$
        Tenure ← randomly select a tabu duration with a probability $p_T$
    end if
    for each neighborhood in Neighborhoods
        neighborList ← ExploreNeighborsAddBestOne(CurrentSolution, neighborhood, Tenure, $\beta etha$)
    end for
    CurrentSolution ← SelectBestNeighbor(neighborList)
    if OF(CurrentSolution) ≤ OF(GRTSIncumbent) then
        GRTSIncumbent ← CurrentSolution
    end if
    $OF_{\beta etha} \leftarrow OF_{\beta etha} + 1/OF(CurrentSolution)$
    $OF_{Tenure} \leftarrow OF_{Tenure} + 1/OF(CurrentSolution)$
    $p_\beta \leftarrow OF_{\beta etha} / \sum_{l=1}^{m} OF_l, \forall \beta etha \in \beta ethas$
    $p_T \leftarrow OF_{Tenure} / \sum_{l=1}^{m} OF_l, \forall Tenure \in Tenures$
end for
return GRTSIncumbent
```

All the parameters recommended by Bernal et al. (2018) are used. It is important to note that the GTS code is used to solve only the supply transports of the real scenario to calibrate the GTS parameters. It is chosen first because it is challenging in a feasible space and second because it is sufficient to demonstrate its usefulness. The last step in the supply routing phase is cutting the routes obtained by the GTS. This methodology is adopted to repair the routes considering the time constraint. Two times are considered to generate the cuts. The first is the travel time from farm A to farm B. For this route, a travel distance is estimated considering the earth's curvature and a cruising speed of 40 km/h is assumed. This issue is because supply routing is performed on tertiary roads, which could be better. The second is a loading time at each farm, which is assumed to be one hour (see Algorithm 2).

4. Computational results

The proposed algorithm is coded in C ++. These experiments are conducted on an 13th Gen Intel® Core™ i9-13980HX (2.20 GHz) on a Windows® 11 operating system with 64 GB of RAM. The efficiency of the phase 3 has been tested on benchmarking instances proposed by Christofides et al. (1979). The best parameter values obtained after the calibration stage were: $TotalIterations = 100$, $GTSIterations = 100$, $Urgencies = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7\}$, $Tenures = \{5, 6, 7, 8, 9, 10, 11\}$, $\beta ethas = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7\}$ and for both algorithms the number of training iterations (*N*) was 30% of total iterations.

The results of the Tables 1 and 2 use the following notation:

- $\boldsymbol{Id}$: reference of the analyzed instance.
- $\boldsymbol{n}$*:* number of customers.
- $\boldsymbol{k}$*:* number of available vehicles at the depot.
- $\boldsymbol{D}$: time constraint for Christofides instances or distance for golden instances per route.
- $\boldsymbol{Q}$*:* capacity of each vehicle.
- $\boldsymbol{BKS}$*:* cost of the best-known solution for DCVRP.
- $\boldsymbol{Reference}$: all reference algorithms: PISM (Taillard, 1993), RT (Rochat & Taillard, 1995), TS (Gendreau et al., 1994), MB (Toklu et al., 2014), CGL (Cordeau et al., 1997), GTS (Toth & Vigo, 2003), PA (Groër et al., 2011), VCGLR (Vidal et al., 2012), CP (Jin et al., 2014), TK (Tarantilis et al., 2002), NB (Nagata & Bräysy, 2009), IBCP (Pecin et al., 2017), MBE (Mester & Bräysy, 2005), LGW (Li et al., 2005), UPSV, ILS-SP, and UHGS (Uchoa et al., 2017).
- $\boldsymbol{Solution}$: cost of the solution that requires only the first two stages or includes the third stage.
- $\boldsymbol{Gap}$: percentage gap of the algorithm solution with respect to the best solution reported in the literature.
- $\boldsymbol{CPU\ Time}$: computation time of the solution expressed in seconds corresponding to the algorithm.

Table 1
Obtained results for the Christofides instances.

Instances details					Best Known Solution		GTS Approach		
Id	n	k	D	Q	BKS	$Reference$	$Solution$	Gap (%)	$CPU\ time\ (s)$
CMT1	50	5	∞	160	524.61	PISM	**524.61**	0.0	5
CMT2	75	10	∞	140	835.26	RT	836.41	0.1	15
CMT3	100	8	∞	200	826.14	TS	827.39	0.2	25
CMT4	150	12	∞	200	1028.42	RT	1030.45	0.2	35
CMT5	199	17	∞	160	1291.29	MB	1300.26	0.7	60
CMT6	50	6	200	140	555.43	PISM	588.67	6.0	1
CMT7	75	11	160	200	909.68	PISM	1092.44	20.1	1
CMT8	100	9	230	200	865.95	PISM	972.70	12.3	1
CMT9	150	14	200	200	1162.55	RT	1457.00	25.3	1
CMT10	199	18	200	200	1395.85	RT	1704.00	22.1	1
CMT11	120	7	∞	200	1042.12	RT	**1042.12**	0.0	33
CMT12	100	10	∞	200	819.56	CGL	**819.56**	0.0	17
CMT13	120	11	∞	200	1541.14	RT	**1541.14**	0.0	22
CMT14	100	11	1040	200	866.37	GTS	1022.80	18.1	87
Average					976.03		1054.25	7.5	23

Tables 1 and 2 show that phase 3 of the proposed approach can find high-quality solutions within short computing times. Note that the former algorithm found some of the best-known solutions reported in the literature (5 instances). Therefore, the complete algorithm has been tested on a real scenario considering different aspects of pineapple cultivation in Colombia. Two motivation aspects have been considered. First, we want to demonstrate the reduction of the logistical cost under the scenario. This fact considers that Colombian idiosyncrasy is an individualism, so cooperative strategies that benefit the grower are not generated. The second motivation is to approximate better the times and costs associated with this phase since, as mentioned in previous sections, there is a strong assumption that the production is collected in the centroid of the municipality. For this reason, a correction is performed since the routing phase is done on a larger scale (productive units). It should be noted that an approach is made on farms with high suitability polygons associated with municipalities that supply IMP demand.

Table 2
Obtained results for the Christofides instances.

Instances details					**Best Known Solution**		**GTS proposed**		
Id	n	k	D	Q	BKS	$Reference$	$Solution$	GAP (%)	$CPU\ time\ (s)$
Golden_1	240	9	650	550	5623.47	PA	6745.25	19.9	16
Golden_2	320	10	900	700	8404.61	VCGLR	10873.48	29.4	57
Golden_3	400	9	1200	900	11036.23	PA	13759.06	24.7	90
Golden_4	480	10	1600	1000	13590	CP	14452.15	6.3	145
Golden_5	200	5	1800	900	6460.98	TK	**6460.98**	0.0	24
Golden_6	280	7	1500	900	8404.06	CP	8413.82	0.1	45
Golden_7	360	8	1300	900	10102.7	VCGLR	11662.01	15.4	65
Golden_8	440	10	1200	900	11635.3	VCGLR	13735.84	18.1	69
Golden_9	255	14	∞	1000	579.71	PA	587.32	1.3	8
Golden_10	323	16	∞	1000	735.66	CP	745.85	1.4	25
Golden_11	399	17	∞	1000	912.03	CP	923.64	1.3	35
Golden_12	483	19	∞	1000	1101.5	CP	1115.2	1.2	86
Golden_13	252	26	∞	1000	857.19	NB	863.6	0.7	15
Golden_14	320	29	∞	1000	1080.55	NB	1092.36	1.1	27
Golden_15	396	33	∞	1000	1337.87	CP	1360.57	1.7	55
Golden_16	480	36	∞	1000	1611.56	CP	1631.69	1.2	61
Golden_17	240	22	∞	200	707.76	NB	709.43	0.2	13
Golden_18	300	27	∞	200	995.13	PA	1011.03	1.6	21
Golden_19	360	33	∞	200	1365.6	PA	1372.22	0.5	31
Golden_20	420	38	∞	200	1817.59	IBCP	1837.69	1.1	60
Average					2488.58		2760.60	3.4	47.4

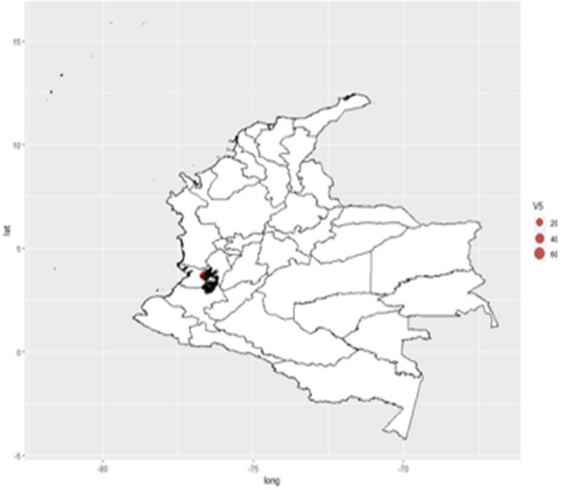

Fig. 8. Location for the IMP 290

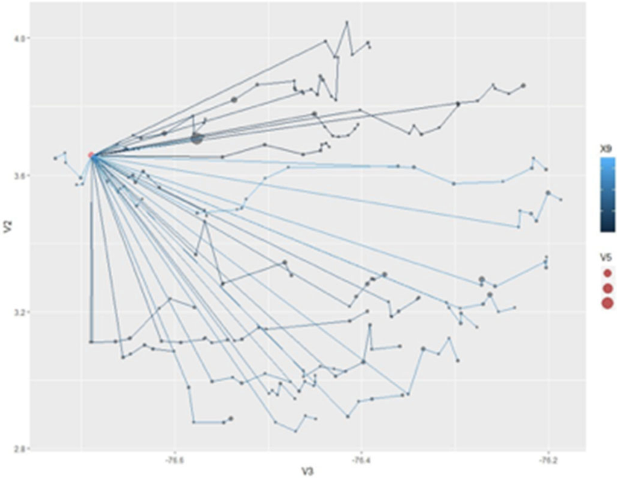

Fig. 9. Location for the IMP 290 and recollection routes

Fig. 8 and Fig. 9 show that an IMP should be opened in the municipality of Dagua, located between the municipalities of Buenaventura, Restrepo, and La Cumbre. This aspect is a perfect location given that it is close to the port and that the farms that cover this IMP are located in neighboring municipalities, so it is feasible to generate routes where the capacity restrictions on vehicles and the distance of the route are met, reducing the associated logistical cost. This IMP covers most of the production of the area of Valle del Cauca, which is why it is the IMP that has the least number of routes and fewer kilometers traveled, making the IMP of Dagua the most profitable of the stage. As a result, 34 routes are obtained where a total of 198 production units are served, with a total distance traveled equal to 4071 kilometers in a time of 101 hours. This aspect represents a reduction of 21% concerning a scenario where farmers send their crops individually. The results of the localization of the IMPs through an optimization model are like the development carried out by Bancoldex and its multicriteria tool (see Fig. 10). However, the presentation of the Bancoldex results is broad since much of the country is suitable for building a platform. The weakness of this analysis is found in the dependence on the subjective qualifications of various experts. Additionally, it does not have an application of resource optimization and compliance evaluation in terms of time coverage.

The department of Santander has the highest current production in Colombia of pineapple; despite this, it only shows a few areas of high suitability according to the UPRA study, which penalized its behavior in the results of the models. The location of the platforms is susceptible to the impacts inherent to transport, although this was only evident after the project's development. It is evident in the behavior of the main costs, that is, those of the grower. IMPs are conceived under a philosophy of improving practices and product quality so that costs can decrease, making pineapple cultivation an attractive and more profitable business.

Currently, it is possible to demonstrate the little individualization of agricultural processes at all economic levels. Given that IMPs are projected to lead the fruit and vegetable industry cooperatively, they can lead to changes in the transport habits of the raw material just after its harvest. In other words, it is highly beneficial to carry out transportation with group productions under the same standards. The proposed solutions have strengths in terms of flexibility and representation of the current context; however, they present weaknesses in the assumptions applied, which can be investigated in future studies.

The proposed hybrid optimization algorithm uses different levels of randomness in both clustering and routing, providing a high level of diversification that allows significant savings to be achieved at the fresh fruit harvesting stage.

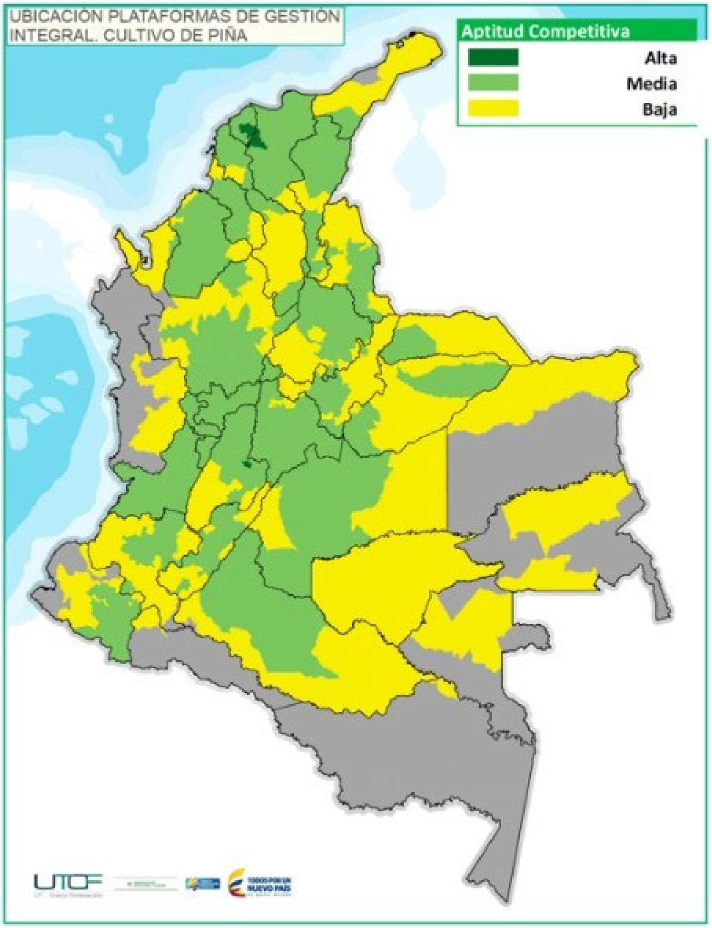

Fig. 10. Location of IMPs for pineapple cultivation (Union Temporal, 2013), High, Medium, and Low

5. Concluding Remarks

This paper proposes a hybrid solution framework to the location routing problem of the pineapple supply chain. A three-phase methodology has been proposed, combining mathematical models and metaheuristic algorithms. The first phase obtains the potential supply and the offer of the product in terms of suitability and productivity. The second phase introduces a mathematical optimization model for the location problem of platforms considering the coverage in terms of timing. Finally, the final phase proposes an urgency cluster-routing algorithm and a granular reactive tabu search approach for the routing phase. The proposed approach has been validated through scenarios, particularly pineapple exports for the Colombian country. The proposed optimization tool is powerful because it can evaluate the implicit variables under different scenarios.

According to the results of the localization model, it is advisable to open IMPs in the departments of Valle del Cauca, Tolima, Cordoba, and Sucre since they cover the two areas with the most significant presence of areas of high suitability, the Caribbean area, and the center, and have good routes for the transport of fresh fruit and are close to the port.

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