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# A planning model of crop maintenance operations inspired in lean manufacturing

Nestor E. Caicedo Solano[a,*], Guisselle A. García Llinás[a], Jairo R. Montoya-Torres[b], Luis E. Ramirez Polo[c]

[a] Department of Industrial Engineering, Universidad del Norte Km 5 Antigua vía a Puerto Colombia, Barranquilla, Colombia
[b] Faculty of Engineering, Universidad de La Sabana, Km 7 Autopista norte de Bogotá, D.C., Chía, Colombia
[c] Department of Industrial Engineering, Universidad Autónoma del Caribe, Calle 90 # 46-112, Barranquilla, Colombia

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ABSTRACT

The operational planning for agricultural production systems become an important tool for decision making for farmers. This paper shows a mathematical model as a decision support tool for crop maintenance planning problems. The model seeks the minimization of waste generated by the use of resources necessary for the task of crop maintenance. The model is inspired on the types of wastes from Lean Manufacturing (LM), which includes labor, use of machinery and operations in time windows that preserve the quality of harvest. The problem is modeled as a Mixed Integer Nonlinear Program (MINLP) in a case study on banana farms in Colombia. The model was tested with different scenarios, operations for crop maintaining, and number of workers. Then, we used the Response Surface Methodology (RSM) for sensitivity analysis, and obtain a significant reduction in cost, resources optimization, wastes, and schedule of crop maintenance activities: a reduction of 59% on the total cost was obtained, as well as a new approach for activities and task scheduling. The contributions of this paper to the body of knowledge in agricultural planning are at least twofold. Firstly, in contrast with traditional modeling approaches, this paper integrates the principles of lean manufacturing (LM) into the definition of parameters and constraints in a mathematical model for crop maintenance. Secondly, the paper couples nonlinear mathematical programming with response surface methodology (RSM) to carry out sensitivity analysis on the results obtained by the mathematical model. It is to note also that, although the modeling and solution methodology follow a case study research approach, it can be applied to other agricultural planning problem at operational level, being an economic option to minimize wastes and resources in others crops.

## 1. Introduction

Farmers and growers of agricultural products, such as fruits and vegetables, often face difficulties for planning resources, times for sowing, maintenance operations, and harvesting that do affect quality and yields in crops, use of water, soils, fertilizations, irrigation, among others. The problem can become even more complex if they need to minimize these resources and to develop sustainable operations. From a traditional planning focus, the farmers must make decisions in regards of production and yields, and sometimes they neglect improvement processes, quality, and productivity. These decisions are at strategic, tactical or operational levels, and contribute in a considerable percentage of the business benefits.

The process of producing agricultural products includes three important stages: sowing, crop maintenance, and harvesting. At every time a new crop is sown, growers must plan activities and resources to keep the crop in optimal conditions for yields and the quality of fruits. After sowing, the crop maintenance is a set of tasks that allow maintaining, intervene and improve the conditions of the plant and its environment, so that they allow an appropriate growth of the crop and subsequent harvest. In an agriculture production system, the crop maintenance work defines part of the success of the whole system; thus giving the importance to assure good yields.

The Food and Agricultural Organization (FAO, 2013) reported that, of the 93 developing countries surveyed, ten are already using more than 40% of their renewable resources for irrigation that is an important

* Corresponding author at: Km 5 Antígua Vía Puerto Colombia, Barranquilla, Colombia.
*E-mail addresses:* nestorc@uninorte.edu.co (N.E. Caicedo Solano), gagarcia@uninorte.edu.co (G.A. García Llinás), jairo.montoya@unisabana.edu.co (J.R. Montoya-Torres), Luis.ramirez@uac.edu.co (L.E. Ramirez Polo).

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activity in crop maintenance. Approximately 80% of increases related to crop production in developing countries will be the result of higher yields, increasing multiple cropping, and shorter fallow periods, and coupled with resource and waste optimization.

In Colombia, a mid-sized developing country, the National Planning Department and the Association of Food Banks conducted a joint study that found about 9.7 metric tons of food (fruits, vegetables, tubers, cereals, grains, and others) are wasted or lost each year. About 22% of the total losses occurred in the agricultural production, post-harvest, storage, and industrial processing stages. Although Colombia is a country with an agricultural vocation that counts on 11.3 million hectares, only 35% (4 million hectares) of this potential is actually in use. In addition, the level of productivity is considered as low. Despite the fact that the agricultural sector is growing faster today than many other economic activities, it has a serious lack of planning. Thus, some Colombian farmers carry out specific agricultural tasks without adequate planning integrated with the needs of crops and soils. Therefore, it is essential to offer a tool for planning the operations of crop maintenance, which aims at the minimum cost of resources to be used. The goal is to preserve quality and productivity. Indeed, this operational planning tool will allow (small) farmers to improve production capacities, generate income, and reduce a percentage of total losses.

According to the previous explained context, the main motivation for developing a model that handles crop maintenance decisions is that profits and losses generated by growers are susceptible of being improved with these short-terms decisions. Among the most important issues in short-term crop maintenance planning are the management of costs in regards of labor, use of water, and machinery, as well as the optimal use of time windows and the preservation of quality and yields. From this scenario, this paper proposes a mathematical model that allows the planning of crop maintenance, with the objective of minimizing the value invested in this stage by farmers to avoid affecting the quality of crops and the future of the harvest. This decision-aid tool is presented as an option for farmers to schedule operations and labor so that costs and wastes are reduced. The proposal is based on the principles of lean manufacturing, which seeks to minimize wastes in labor, transport, quality, stocks, as well as minimize waiting times, overprocessing, and overproduction. This is hence the main contribution of this paper: the integration of lean manufacturing principles into a mathematical model to aid decision-making in crop maintenance for the reduction of wastes and losses in labor, times and quality.

To show the applicability of the proposed model, this paper presents a case study on banana famers in Colombia. This crop was selected because the economic importance and production volume among fruits and vegetables that Colombia exports, in addition to the complexity that this process adds to the modeling approach due to the multiplicity of activities. An advantage of using this case study is that the mathematical model and its solution method are complex enough to be easily adapted to other crops, such as plantain, oil palm, papaya, and others.

There rest of this paper is organized as follows. Section 2 gives a background on overview of the literature in agricultural production problems and lean manufacturing. Section 3 describes the mathematical model. Data for the experiments, computational results, and the application of the response surface method for sensibility analysis are presented in Section 4. Finally, conclusions, discussions and some opportunities for future research are outlined in Section 5.

## 2. Literature review

To the best of our knowledge, the academic literature about operational planning for crop maintenance is scarce. Academic works on the application of optimization techniques from the Operational Research to solve crop maintenance-planning problems focus on the previous stage for harvesting. Indeed, most of such works focus on harvesting decisions and few authors consider crop maintenance decisions. Additionally, the problems found in the literature are not based in Lean Manufacturing principles as a tool to reduce wastes and cost. There are some publications on physiological, chemical, and physical aspects that analyze the growth and maintenance of crops but without implying the optimization in the process, the waste reduction or the planning and operational scheduling of activities and resources for the different crop maintenance tasks. However, other authors have made different contributions to diverse topics related to crop maintenance, for example in water management as one of the most restrictive resources. Xu et al. (2014) presented mathematical models that were used to solve the optimal consumption of water.

Other approaches to production control have been proposed. Some studies have optimized the harvest quantities and yields using mathematical models based in mixed-integer nonlinear programming (MINLP) for the scheduling of operations in crops (Blanco et al., 2010; Sha-sha et al., 2013). Adham et al. (2016) illustrated the use of rainwater to optimize its consumption by crops. Edwards et al. (2015; Zhou et al., 2015) solved problems in agricultural production systems such as rock removal operations, planting, and irrigation. Thuankaewsing et al. (2015) developed a work on waste reduction based on costs associated with waste in harvest operations. Vema et al. (2019) developed a fuzzy logic model applying a fuzzy inference system (FIS) for the selection of the suitable rainwater harvesting structure owing to its capability to handle linguistic data.

Moreover, many research about the management of crop can be found depending on the fruit that has been analyzed and their characteristics. Hester and Cacho (2003) worked in the modeling to solve crop-mixing problems and the modeling of the biological conditions of perishables. Recio et al. (2003) built decision-making models regarding cereal crops as well as sugar beet and vegetables. Caixeta-Filho (2006) presented a model for the scheduling of orange fruits, (Li et al., 2012) studied the tactical and operational crop planning of apples and pears to develop theoretical models with some real approaches, and Higgins & Laredo (2006) focused on the improvement of harvesting sugar cane. Also, most recently, research has focused on the application of Industry 4.0 tecnologies different devices and technologies 4.0 looking for perfect control of the system to differences changes.

Although management in the agriculture process has been widely investigated, the mathematical models applied to this process are relatively less. (Lowe & Preckel, 2004) presented a clear explanation of how these models work, their different applications, and what the future would be like in their time. Other authors like (Biswas & Pal, 2005) design a model to crop planning that prioritizes the minimization of inputs. (Arnaout & Maatouk, 2010) solved the problem of evaluating the costs associated with the operations in the fields. (Sethanan & Neungmatcha, 2016) worked a model successfully applied; this included the minimization of the timing on operations and the use of machinery in manual and mechanical harvesting operations, and (Mardani Najafabadi et al., 2019) design an optimization model of regional cropping pattern decisions in 23 counties of an Arabic province through Multi-Objective Structural Planning (MOSP) with different objectives, such as economic, social, and environmental. Due to their complexity, non-linear models and especially the mix integer nonlinear models are less used in this field, however, to make these models more real, it is necessary to work on them, authors such (Zhang & Guo, 2018) developed two-stage mixed-integer linear for agricultural water management under uncertainty considering ecological water requirement considering and economic benefits and risk in the objective function simultaneously, (Cervantes-Gaxiola et al., 2020; Zhang et al., 2018) used another model with the same characteristics for crop area planning under uncertainty to the objective of supporting irrigation water management under arid and semiarid environments. (Mardani Najafabadi et al., 2019) developed a model of spreading scheduling to improve soil organic carbon content to considering the composts and mineral fertilizers from agriculture with an MINLP model subjected to certain operational, regulatory, and soil-dynamics constraints, maximizing the total estimated profit. Also more recently, an integer multi-objective non-linear programming model incorporating intuitionistic fuzzy numbers for agricultural water and land resources allocation involving economic, environmental, and social dimensions, was developed by (Li et al., 2020). (Cid-Garcia & Ibarra-Rojas, 2019) addressed an MINLP model to maximize the total expected profit of the farmer based on crop planting, considering partitioning the agricultural fields into chemical and physical management zones satisfying a specific homogeneity level according to the soil properties and considers the management zones, to determine the best crop for each plot.

In the same way, increasingly used different methodologies are used to be more efficient in agricultural processes, one more used in Lean methodology. For example (Lermen et al., 2018) presents techniques and methodologies used for the agro-industrial sector, towards the development of products supported by Lean practices and his tools, increasing the preservation up to 25% higher yield compared to the current best preserving solution. (Pearce et al., 2018) make research on determining factors that drive sustainable performance through the application of lean methods in the primary production segment of the horticultural supply chain for apples and pears in the Western Cape of South Africa. (Barth & Melin, 2018; Reis et al., 2018) proposes different Lean Implementation Framework in which small and mid-size farms that applying various Lean tools can increase production and profit and yet support environmental sustainability. Similarly, In his research (Muñoz-Villamizar et al., 2019) analyze gaps and trends existing of lean and green in the agri-food sector and the integration between them. Finally, (Caicedo Solano et al., 2020) concluded that the literature on the agricultural planning, sowing, crop maintenance and harvesting lack integration of the environmental and climatic factors, product quality, minimization of wastes and operational efficiency of agricultural production systems, additionally, no tools are used to manage farms as they are used in other companies. We found an opportunity for using this tools for reduction of wastes, therefore, we propose the use of MINLP integrated to LM as a tool for reducing cost, scheduling task, labor, times, all involved in the seven types of wastes of lean manufacturing that historically have been successful in other production systems.

## 3. Methods and procedures

### 3.1. Model description

The crop maintenance planning problem considered in this paper consists of a number of hectares for maintaining, a set of activities or works for maintenance, and periods for planning. In this case it is desirable to minimize wastes generated for labor, machinery, agricultural supplies, movements, and operations. Additionally is preserved the quality of the crop and the fruits that can be harvested. The objective function seeks to reduce the cost of crop maintenance, as well as allocate resources and work scheduled in the agricultural production system. The model assumptions, sets, parameters and decision variables are described below:

**Assumptions.** 1. *The hectares that will maintain are known.*
2. *The costs associated with cultivation work are known.*
3. *Operation times and runtime windows of tasks are known.*
4. *It is known the effect of failures in cultivation work that may affect growth or subsequent harvest.*
5. *In many crops, maintenance operations must be carried out within optimal time windows to avoid damage to the plants. However, maintenance operations must be carried out even outside the optimal time windows, what happens is that it is possible that the costs associated with the operations or caused to the quality of the production is higher in any case. The hectares served are presented in the decision variables since this can or cannot be done within the optimal time windows; this cost could affect the objective function.*

Notations

| | |
|---|---|
| Indexes | |
| i | Hectares for maintaining. i = 1,2,3,4,…I. |
| j | Stages of process (fertilization, irrigation, weed control, etc.), j = 1,2,3,4…J. |
| t | Planning period, t = 1,2,3,4….T. |
| Parameters | |
| $T_{i,j}$ | Time to maintain a hectare i in stage j. |
| $D_{i,t}$ | Hectare i that requires labor maintenance in period t. |
| $C_i$ | Cost for servicing hectare i in an optimal time window. |
| $CE_i$ | Cost for servicing hectare i in non-optimal time window. |
| $DH_t$ | Business day in period t |
| $HC_j$ | Hours per crew for labor j |
| $TP_{j,t}$ | Time lost by machinery in stage j in period t (irrigation system, weed control equipment, etc.) |
| $CC_j$ | Cost of hiring a worker for processing stage j |
| $CD_j$ | Cost of firing a worker for processing stage j |
| $CTP_j$ | Cost per time lost by machinery used in process j |
| Decision Variables | |
| $X_{i,t}$ | Number of hectares i to serve in the normal period t (optimal time window) |
| $XE_{i,t}$ | Number of hectares i to serve in the extemporaneous period t (non-optimal time window) |
| $E_{j,t}$ | Number of workers available for stage j in period t |
| $EC_{j,t}$ | Number of workers to hire for stage j in period t |
| $ED_{j,t}$ | Number of workers to be fired in stage j in period |
| Binary Decision Variables | |
| $\Omega_{1t}$ | 1 if work shift 1 is activated for period t, 0 otherwise |
| $\Omega_{2t}$ | 1 if work shift 2 is activated for period t, 0 otherwise |
| $\Omega_{3t}$ | 1 if work shift 3 is activated for period t, 0 otherwise |

### 3.2. Mathematical model

$$\textbf{\textit{MinZ}} = \sum_i\sum_j\sum_t(C_i{}^*X_{it} + CE_i{}^*XE_{it} + CC_j{}^*EC_{jt} + CD_j{}^*ED_{jt} + CTP_j{}^*TP_{jt})$$

Subject to:

$$\sum_i T_{ij}{}^*X_{it} - (\Omega_{1t} + \Omega_{2t} + \Omega_{3t})^*\mathrm{DH}_t{}^*HC^*\mathrm{E}_{jt} + \mathrm{TP}_{jt} \leq 0\forall_j \in J, \forall_t \in T$$

$$\sum_i T_{ij}{}^*XE_{it} - 2(\Omega_{1t} + \Omega_{2t})^*DH_t{}^*E_{jt} \leq 0, \forall_j \in J, \forall_t \in T \quad (2)$$

$$(\Omega_{1t} + \Omega_{2t} + \Omega_{3t}) = 2, \forall_t \in T \quad (3)$$

$$E_{(j-1)t} + EC_{jt} - ED_{jt} = E_{jt}, \forall_j \in J, \forall_t \in T \quad (4)$$

$$X_{it} + XE_{it} = D_{it}, \forall_i \in I, \forall_t \in T \quad (5)$$

$$XE_{it} \geq 0, \forall_i \in I, \forall_t \in T \quad (6)$$

$$X_{it} \geq 0, \forall_i \in I, \forall_t \in T \quad (7)$$

For this model is important to consider that all activities for crop maintenance must be carried out. The objective function seeks to minimize the total cost of operations implicitly reducing wastes. Constraints (1) to (7) evaluate the necessary conditions of crop maintenance. Constraints (1) corresponds to the requirement of minimal time lost due to maintenance work on the crop. Constraints (2) indicate the requirements to perform work in optimal time windows; these constraints guarantee that the time do not exceed available time for the operations in optimal time windows. Constraints (3) consider the activation of shifts or work crews of crop maintenance, in this case the model decides between 2 crews out of 3 crews available. With Constraints (4) the work is defined in a given time with available workers. Constraints (5) determine the number of workers to serve the total hectares that require maintenance. Constraints (6) and (7) correspond to the values of decision variables.

## 4. Experiments and numerical setting

### 4.1. Case study and input data

This section presents the validation of the mathematical model on a case study of bananas in Colombia to illustrate its applicability to practical problems in agricultural production. In order to reduce production costs and to increase sustainability and productivity, farmers in Colombia have worked on waste reduction and fruit quality improvement. Moreover, the arrival of Fusarium Oxysporum Tropical Race 4 (TR4) have forced those growers to concentrate their efforts on prevention, which has increased production costs on almost 100 million boxes (2,1 tons of production and 1,9 tons for exports) in 2019. Now, the area of the farms is about 15.000 ha in Caribbean region of Colombia, illustrated in Fig. 1. Among the most important task of the farms, sowing, planting renovation, crop maintenance, harvesting, packing, transportation, distribution and exportation to markets in Europe, Asia and USA.

Banana varieties cultivated in Colombian farms is of the Cavendish family, the most exported and most commonly eaten fresh in three clones known as Williams, Valéry and Grand Naine. This means that production costs can vary from farm to farm and within farms. For this reason, the model considers hectares to produce and some operations in crop maintenance.

For the purpose of the numerical analysis, values of sets and parameters to feed the mathematical model is taken from bananas farms. They work only 2 or 3 days per week, which means that during these days the crop is maintained and harvested. It is important to clarify that current practices for crops maintenance tasks are done following a traditional approach without implementing any formal decision-making support tool, so this is a non-optimal time window that could affect the specifications of fruits and generates additional costs for growers. Data employed for the numerical validation on this case study is presented in Table 1. Data employed to run the model was collected between January 2018 and January 2020, considering that bananas has not specific season for production.

Table 2 and 3 presents the cost of operations, respectively, in optimal and non-optimal time windows.

The model was coded on GAMS® version 24.4.6 for x86 64bit/MS Windows. The solver used was Couenne-OR, an exact solver for non-convex MINLPs included in GAMS library. Experiments were run on a personal computer with processor Intel® Core™ i5-5300 CPU 2.3 Ghz, 8 GB of RAM and hard drive of 500 GB. After compilation, the size of this instance generated had 97 single equations, 9 blocks of variables, 145 single variables, 607 non zero elements, 126 nonlinear n-z, 20 derivate pool, 18 constant pool, and 144 discrete variables.

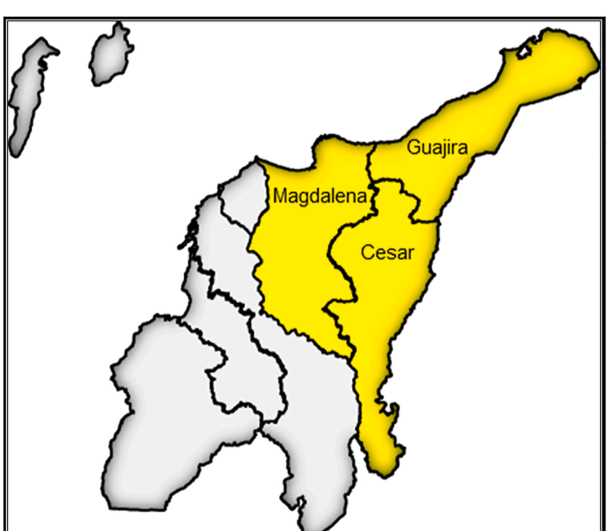


**Fig. 1.** States of Caribbean Region of Colombia where Bananas is produced.

**Table 1**
Input data for the numerical validation.

| Indexes | Notation | Meaning | Values |
|---|---|---|---|
| | i | | 1, 2, 3, 4, 5, 6 |
| | j | | 1 = fertilization 2 = irrigation 3 = weed control |
| | t | | 1, 2, 3, 4, 5, 6 |
| Parameters | $T_{i,j}$ | Time for maintain a hectare i in stage | 3 h |
| | $D_{i,t}$ | Areas/ lots i that requires maintain labor in period t | 8 |
| | $C_i$ | Cost per attention a hectare i in optimal time window | US$ 12 |
| | $CE_i$ | Cost per attention a hectare i in non - optimal time window | US$ 21 |
| | $DH_t$ | Business day in period t | 3 days / week |
| | $HC_j$ | Hours per crew for labor j | 4 / day. |
| | $TP_{j,t}$ | Time lost by machinery in stage j in period t (irrigation, weed control equipment) | 1 h max. |
| | $CC_j$ | Cost of hiring a person for the process stage j | US$ 12 |
| | $CD_j$ | Cost of firing a person for the process stage j | US$ 16 |
| | $CTP_j$ | Cost per time lost by machinery used in stage j | US$ 20 |

**Table 2**
Elements of cost for task in optimal time window.

| Elements | Cost (US$) |
|---|---|
| Hiring a worker for operation / day /Area | 12 |
| Firing a worker for operation / day /Area | 16 |
| Wasted hour of machinery | 20 |
| Logistic cost for attention a hectare | 12 |

**Table 3**
Elements of cost for task in non-optimal time window.

| Elements | Cost (US$) |
|---|---|
| Hiring a worker for operation / day /Area | 12 |
| Firing a worker for operation / day /Area | 16 |
| Wasted hour of machinery | 20 |
| Logistic cost for attention a hectare | 15,6 |

### 4.2. Analysis of results

This section presents the results obtained after applying the proposed mathematical model. For the purpose of the analysis, all cost values have been converted to US Dollars. In comparison with the current situation, implementing the solution of the mathematical model would allow a reduction of 59% of the best solution. The best solution is US$ 11.728; the total cost is minimized with a reduction of wastes resources allocated for crop maintenance. The main results are presented next. Table 4 indicates the work shift for days of work, while Table 5 indicates the hectares or lots to be served in non-optimal time windows. Table 6 presents the number of workers fixed for each stage in a period, and Table 7 shows the number of workers to be hired for each stage in a period.

To illustrate the optimization obtained through this model, we present some scenarios of cost for crop maintenance tasks with six workers available for tasks. Tables 8 and 9, respectively presents the results of the scenario with optimal and non-optimal time windows, but without

**Table 4**
Work shift schedule.

| Days / week | Work shift activation | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| 1 | Active | Active | Inactive |
| 2 | Active | Active | Inactive |
| 3 | Inactive | Active | Inactive |
| 4 | Active | Active | Active |
| 5 | Inactive | Active | Active |
| 6 | Inactive | Active | Active |

**Table 5**
Number of hectares for maintenance.

| Areas or lots | Days for planning | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 8 | 8 | 8 | 8 | 8 | 8 |
| 2 | 8 | 8 | 8 | 8 | 8 | 8 |
| 3 | 8 | 8 | 8 | 8 | 8 | 8 |
| 4 | 8 | 8 | 8 | 8 | 8 | 8 |
| 5 | 8 | 8 | 8 | 8 | 8 | 8 |
| 6 | 7(1)* | 7(1)* | 8 | (8)* | 8 | 8 |

* The value in parenthesis (X) represents the number of hectares for attending in an optimal time window.

**Table 6**
Number of person available for stage.

| Stages | Period | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 4 | 4 | 4 | 4 | 4 | 4 |
| 2 | 4 | 4 | 5 | 4 | 5 | 5 |
| 3 | 6 | 6 | 6 | 5 | 6 | 6 |

**Table 7**
Number of workers to hire.

| Stages | Period | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 4 | 4 | 4 | 4 | 4 | 4 |
| 2 | – | – | 1 | – | 1 | 1 |
| 3 | 2 | 2 | 1 | 1 | 1 | 1 |

optimization. We can note in Table 9 that the total cost for this scenario is greater than the best solution obtained in mathematical model.

To build a sensitivity analysis, a response surface methodology (RSM) was developed, in order to predict the minimum value of the objective function for activities per week. Data were analyzed in Minitab 19®. Table 10 presents the results. The best solution value was Zmin (Response) of US$ 4.710 in optimal time window. The optimization of responses is illustrated in Fig. 2. Maintenance operations, areas to maintain, workforce, time crews, and wastes are represented as levels for the RSM. Two levels were chosen for RSM, the maximum level is depicted as "Alto" in the Figure, while the minimum level as "Bajo" in the Figure. The red values are optimal levels that minimize the total cost for the mathematical model. The minimum cost calculated by RSM is expressed as variable "Y". Fig. 2 illustrates the optimal values for minimizing the total cost in one week.

The resources can be scheduled in next weeks for covering the areas required. With this option, the best cost is US$ 4.710. For this case is possible to perform two stages per week, serve four areas or lots, working five days per week, six hours per day for crew time (workers) and one hour for wasted machinery. However, crop maintenance tasks can be modified according to the needs of each farm, taking into account that crops can change their physical, chemical and biological conditions due to uncontrollable factors (weather conditions, good agricultural

**Table 8**
Current scenario without optimization model in optimal time window.

| Maintenance operations | Area maintenance | Working Days | Time Crews | Wasted time of Machinery | Total Cost (US $) |
|---|---|---|---|---|---|
| 2 | 4 | 3 | 4 | 1 | $ 4.968 |
| 4 | 4 | 3 | 4 | 1 | $ 6.264 |
| 2 | 8 | 3 | 4 | 1 | $ 7.560 |
| 4 | 8 | 3 | 4 | 1 | $ 8.856 |
| 2 | 4 | 5 | 4 | 1 | $ 13.800 |
| 4 | 4 | 5 | 4 | 1 | $ 17.400 |
| 2 | 8 | 5 | 4 | 1 | $ 21.000 |
| 4 | 8 | 5 | 4 | 1 | $ 24.600 |
| 2 | 4 | 3 | 6 | 1 | $ 4.968 |
| 4 | 4 | 3 | 6 | 1 | $ 6.264 |
| 2 | 8 | 3 | 6 | 1 | $ 7.560 |
| 4 | 8 | 3 | 6 | 1 | $ 8.856 |
| **2** | **4** | **5** | **6** | **1** | **$ 13.800** * |
| 4 | 4 | 5 | 6 | 1 | $ 17.400 |
| 2 | 8 | 5 | 6 | 1 | $ 21.000 |
| 4 | 8 | 5 | 6 | 1 | $ 24.600 |
| 2 | 4 | 3 | 4 | 2 | $ 6.048 |
| 4 | 4 | 3 | 4 | 2 | $ 7.344 |
| 2 | 8 | 3 | 4 | 2 | $ 8.640 |
| 4 | 8 | 3 | 4 | 2 | $ 9.936 |
| 2 | 4 | 5 | 4 | 2 | $ 16.800 |
| 4 | 4 | 5 | 4 | 2 | $ 20.400 |
| 2 | 8 | 5 | 4 | 2 | $ 24.000 |
| 4 | 8 | 5 | 4 | 2 | $ 27.600 |
| 2 | 4 | 3 | 6 | 2 | $ 6.048 |
| 4 | 4 | 3 | 6 | 2 | $ 7.344 |
| 2 | 8 | 3 | 6 | 2 | $ 8.640 |
| 4 | 8 | 3 | 6 | 2 | $ 9.936 |
| 2 | 4 | 5 | 6 | 2 | $ 16.800 |
| 4 | 4 | 5 | 6 | 2 | $ 20.400 |
| 2 | 8 | 5 | 6 | 2 | $ 24.000 |
| 4 | 8 | 5 | 6 | 2 | $ 27.600 |
| 3 | 6 | 4 | 5 | 1,5 | $ 13.248 |

* The total cost for this scenario is greater than the best solution obtained with mathematical model.

practices and compliance with quality production in production).

Besides, a comparison between possible real scenarios in current conditions for farmers, as well as the best solution of the mathematical model and response surface methodology is presented in Fig. 3. The best scenario is proposed from mathematical model; however, the scenario with RSM is possible, but farmers must strive to allocate and schedule resources according to the needs of the farm.

## 5. Conclusions and future research

In Colombia, the complexity of producing bananas is very relevant, more than 90% of production is for international markets. Markets not only require compliance with trade conditions, they also require quality and productivity, due to the increase in demand in the last decade. This paper proposed a non-linear mathematical model to minimize production costs while dealing with waste reduction. To focus to reduce waste was on the integration of lean manufacturing principles when applied to crop maintenance in agricultural production. A numerical validation is presented on a case study of banana production in Colombia. A sensitivity analysis was also carried out employing a response surface methodology.

Although implemented on a case study, the proposed model can be applied to different types of crops and farms that produce fresh fruit. So, it is useful to support operational decision-making and can be saw as tool for minimizing wastes in agricultural production systems. Indeed, the model allow for planning the resources of labor, times for operations, areas for maintenance, use of machinery, seeking to minimize the production costs for farmers and producers. Actors of the agricultural

**Table 9**
Current scenario without optimization model in non-optimal time window.

| Scenario in Non - Optimal Time Window | | | | | |
|---|---|---|---|---|---|
| Maintenance operations | Area maintenance | Working Days | Time Crews | Wasted time of Machinery | Total Cost (US $) |
| 2 | 4 | 3 | 4 | 1 | $ 5.746 |
| 4 | 4 | 3 | 4 | 1 | $ 7.042 |
| 2 | 8 | 3 | 4 | 1 | $ 9.115 |
| 4 | 8 | 3 | 4 | 1 | $ 10.411 |
| 2 | 4 | 5 | 4 | 1 | $ 15.960 |
| 4 | 4 | 5 | 4 | 1 | $ 19.560 |
| 2 | 8 | 5 | 4 | 1 | $ 25.320 |
| 4 | 8 | 5 | 4 | 1 | $ 28.920 |
| 2 | 4 | 3 | 6 | 1 | $ 5.746 |
| 4 | 4 | 3 | 6 | 1 | $ 7.042 |
| 2 | 8 | 3 | 6 | 1 | $ 9.115 |
| 4 | 8 | 3 | 6 | 1 | $ 10.411 |
| **2** | **4** | **5** | **6** | **1** | **$ 15.960** * |
| 4 | 4 | 5 | 6 | 1 | $ 19.560 |
| 2 | 8 | 5 | 6 | 1 | $ 25.320 |
| 4 | 8 | 5 | 6 | 1 | $ 28.920 |
| 2 | 4 | 3 | 4 | 2 | $ 6.826 |
| 4 | 4 | 3 | 4 | 2 | $ 8.122 |
| 2 | 8 | 3 | 4 | 2 | $ 10.195 |
| 4 | 8 | 3 | 4 | 2 | $ 11.491 |
| 2 | 4 | 5 | 4 | 2 | $ 18.960 |
| 4 | 4 | 5 | 4 | 2 | $ 22.560 |
| 2 | 8 | 5 | 4 | 2 | $ 28.320 |
| 4 | 8 | 5 | 4 | 2 | $ 31.920 |
| 2 | 4 | 3 | 6 | 2 | $ 6.826 |
| 4 | 4 | 3 | 6 | 2 | $ 8.122 |
| 2 | 8 | 3 | 6 | 2 | $ 10.195 |
| 4 | 8 | 3 | 6 | 2 | $ 11.491 |
| 2 | 4 | 5 | 6 | 2 | $ 18.960 |
| 4 | 4 | 5 | 6 | 2 | $ 22.560 |
| 2 | 8 | 5 | 6 | 2 | $ 28.320 |
| 4 | 8 | 5 | 6 | 2 | $ 31.920 |
| 3 | 6 | 4 | 5 | 1,5 | $ 15.322 |

**Table 10**
Prediction for multiple responses.

| Variable | Configuration values |
|---|---|
| Maintenance operations | 2 |
| Area maintenance | 4 |
| Working days | 5 |
| Time crew | 6 |
| Wasted time of machinery | 1 |

supply chain will find the proposed approach useful to manage farms by implementing a management philosophy based in lean manufacturing principles coupled with mathematical modeling. This plan must be executed efficiently from the beginning of the sowing stages considering that the areas to be cultivated and the expected yields of the harvest known. With this plan it is also possible to estimate the costs related to the operation, so that decisions can be made as the environmental, chemical, physical or physiological conditions of the crop change or require operational adjustments. Although non-linear, the complexity of the problem and the solution methods required low computational time, as well as low usage of computational resources, which enables it use in real practical settings.

In many farming environments, and especially in Colombia, planning agricultural production is done based on the experience and practical knowledge of managers or farmers; moreover, data is collected but not properly analyzed, which results in frequent planning errors that causes higher operational costs in crop maintenance, and risks in fruits quality. The proposed optimization model serves hence as a decision-aid tool.

An additional contribution of the present model is the reduction of wastes in agricultural production, thus contributing to its sustainability thanks to the direct impact that this reduction has on the intervention and use of natural resources. This contribution is paramount, since most optimization models in the literature focus on cost minimization.

As opportunities for future research, it is important to include other aspects such as distances traveled, statistical analysis of inventories of unserved plants, and the correlations between climate conditions and crop needs patterns, to maintain fruit quality. Secondly, it can be interesting to evaluate the environmental impact, especially for transport logistics in farms, and the use of natural resources as such water and soil. Dynamic Programming, precision agriculture, simulation, and quantitative tools can aid to solve these problems. Finally, we would like to mention the opportunity to work on the integration of these tools in future research is significant, promising results and benefits to farmers.


**Fig. 3.** Total cost for scenarios.

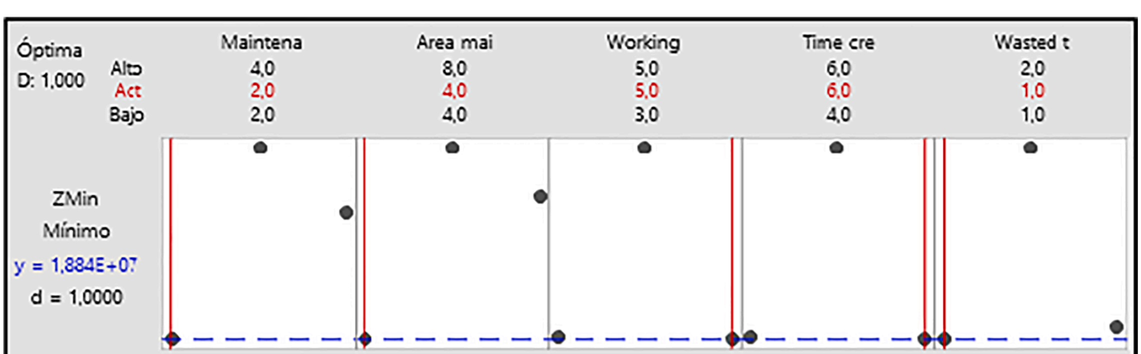


**Fig. 2.** Levels of response surface for best cost.

## Declaration of Competing Interest

The authors declared that there is no conflict of interest.


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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2020.105852.

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